

# **Recent Results from the STAR Experiment at RHIC**

Nu Xu  
Lawrence Berkeley National Laboratory

*Many Thanks to the Organizers*



# Outline

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## 1) Introduction

## 2) STAR Experiment at RHIC

- Status of the experiment
- Recent results (selected)

## 3) Near future programs



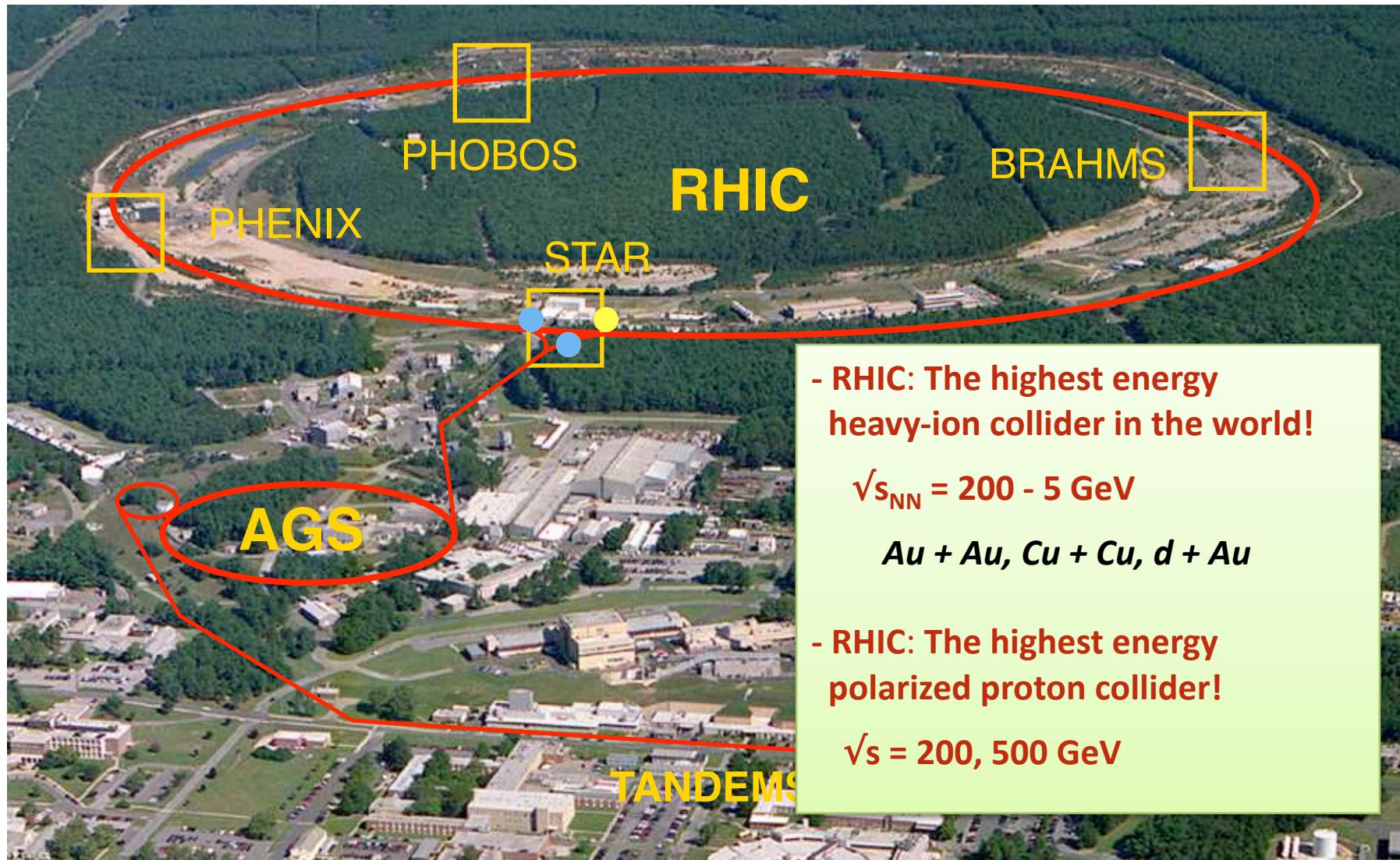
# Physics Goals at RHIC

- Identify and study the properties of matter (EOS) with partonic degrees of freedom in high-energy nuclear collisions.
- Explore the QCD phase diagram.



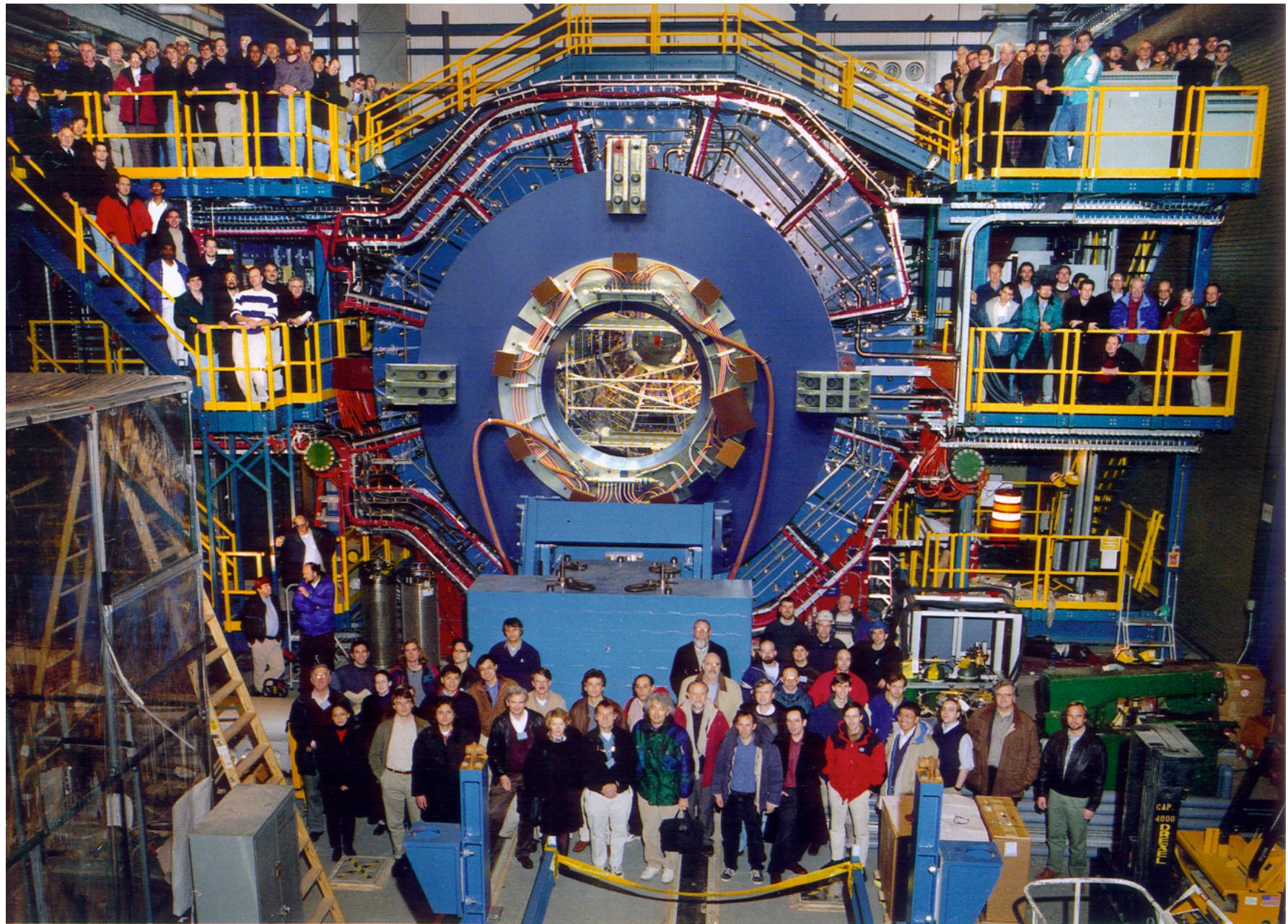
# Relativistic Heavy Ion Collider (RHIC)

Brookhaven National Laboratory (BNL), Upton, NY

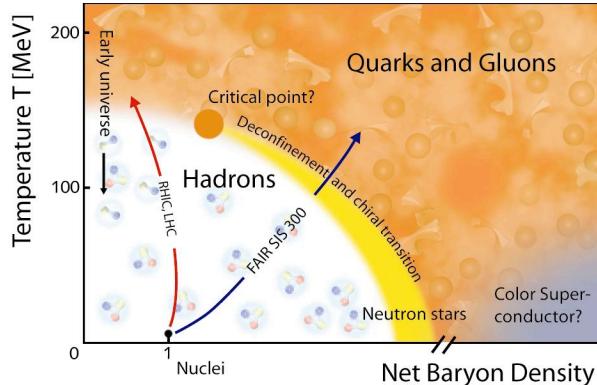




# STAR Experiment



# STAR Physics Focus

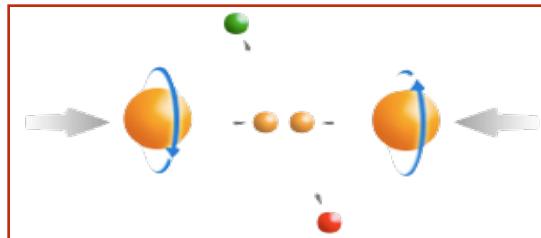


## 1) Heavy-ion program at top energy

- Study ***medium properties, EoS***
- pQCD in hot and dense medium

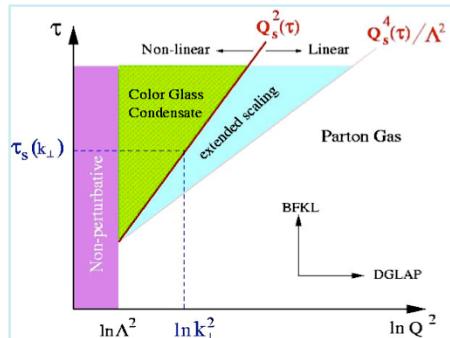
## 2) RHIC beam energy scan

- Search for ***critical point***
- Chiral symmetry restoration



## Polarized spin program

- Study ***proton intrinsic properties***

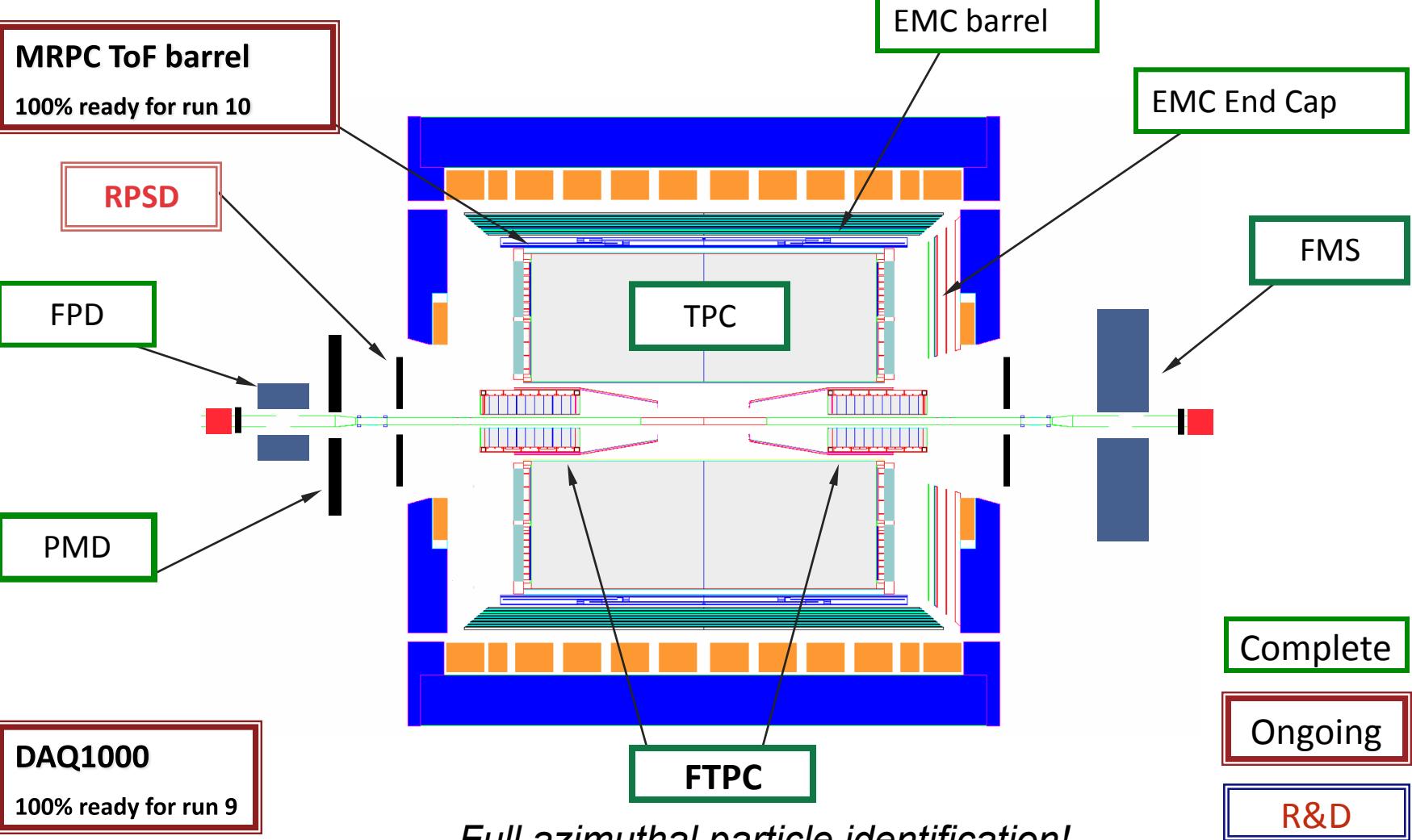


## Forward program

- Study low-x properties, search for ***CGC***
- Study elastic (inelastic) processes (pp2pp)
- Investigate ***gluonic exchanges***

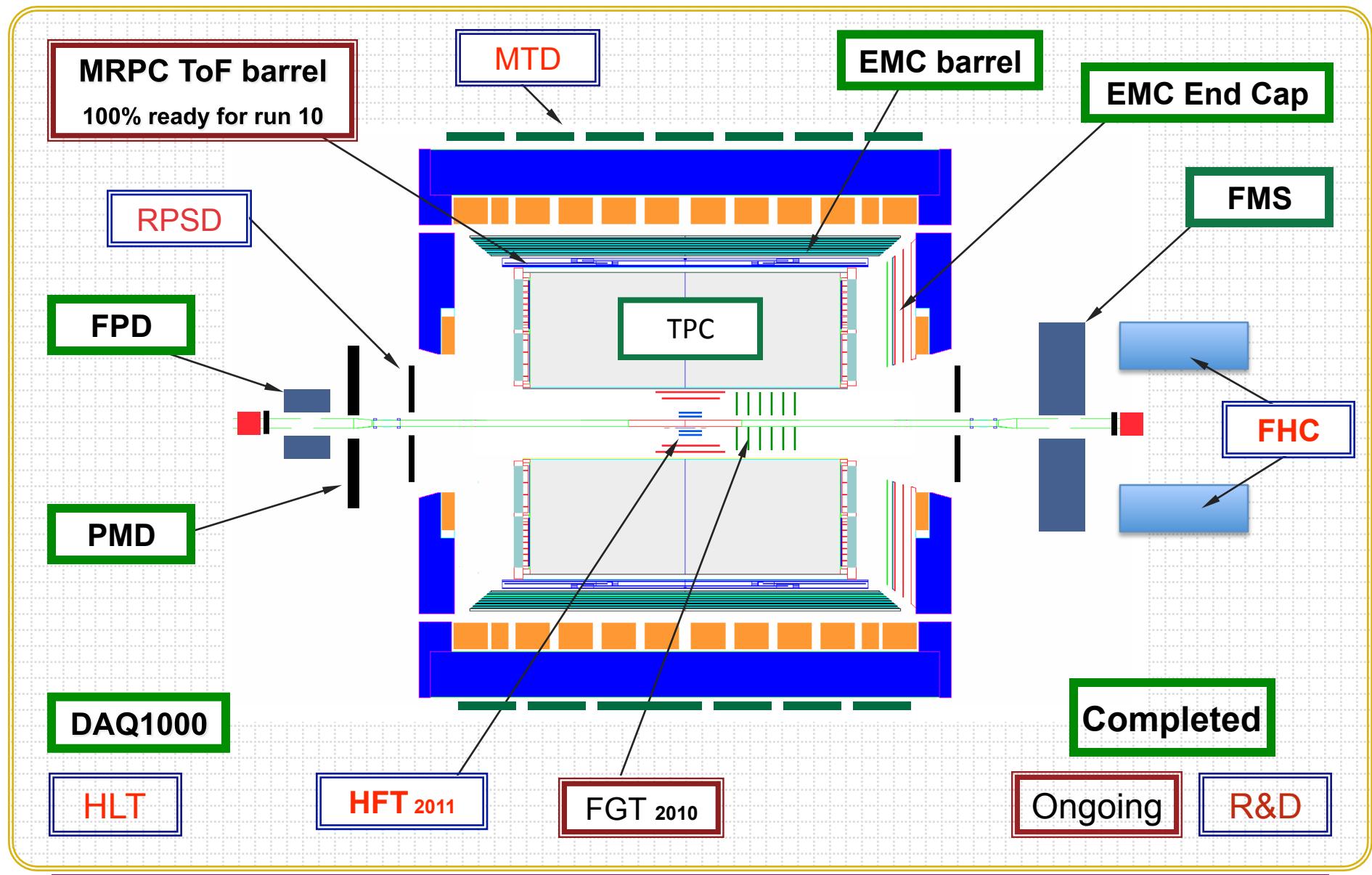


# STAR Detector



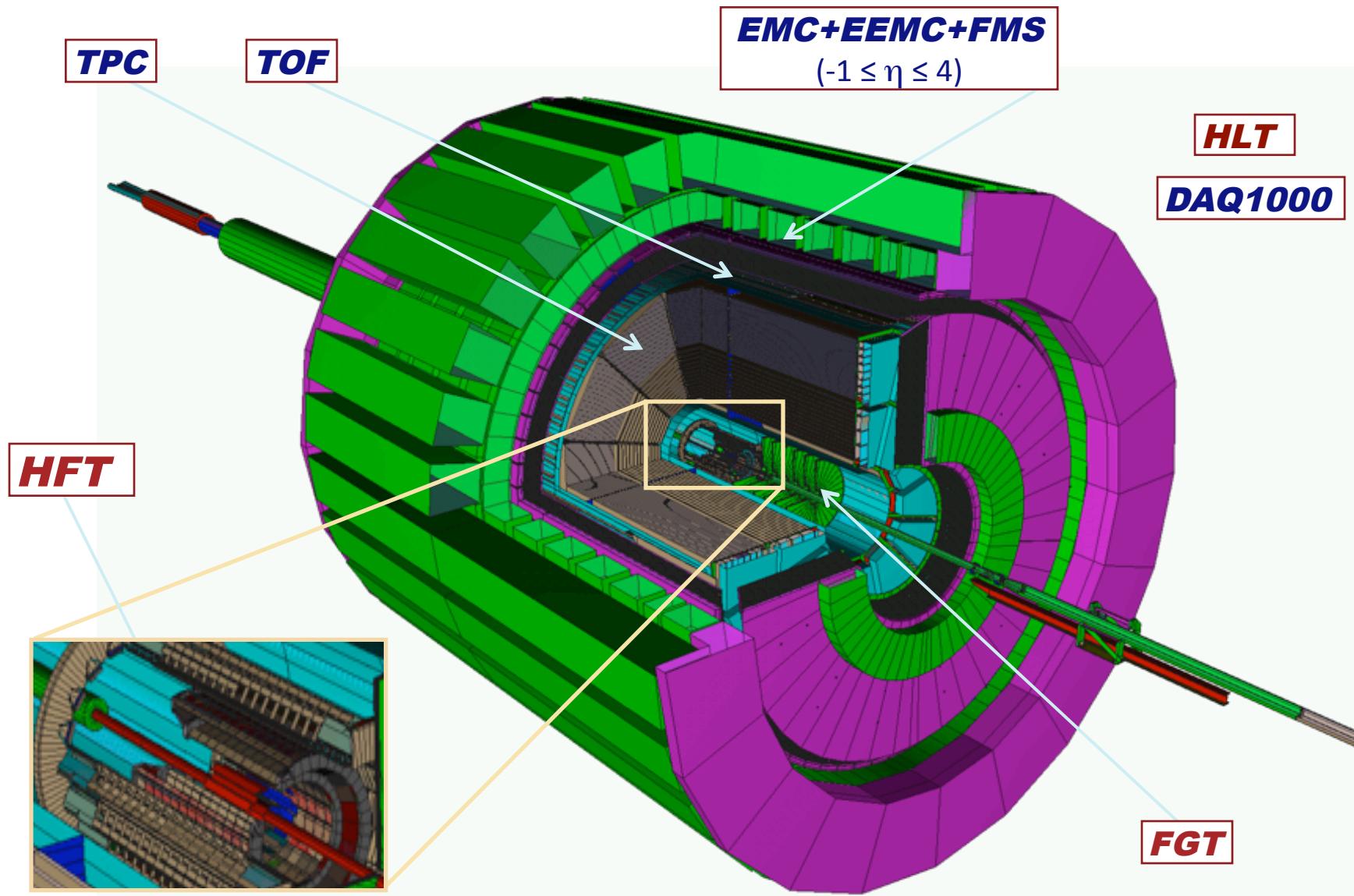


# STAR Detector

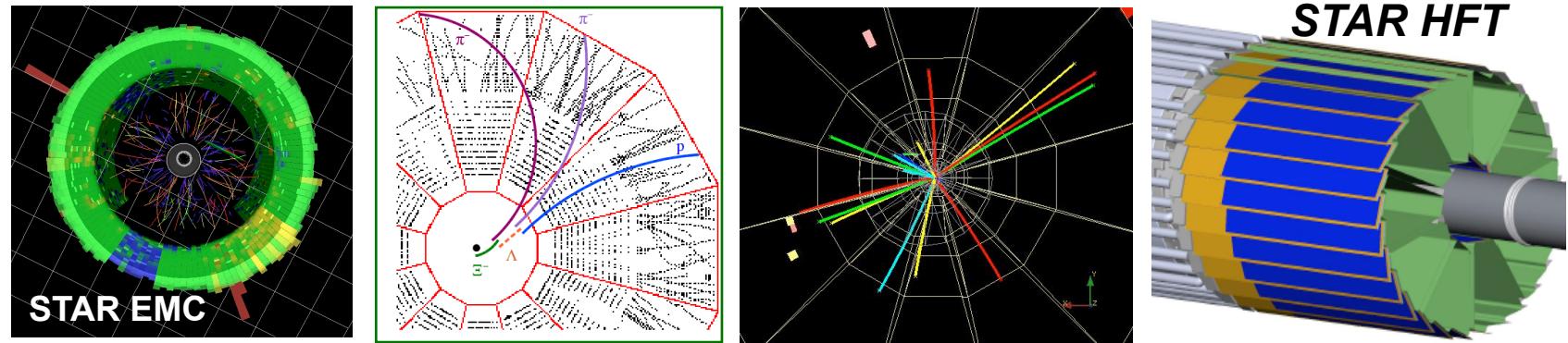
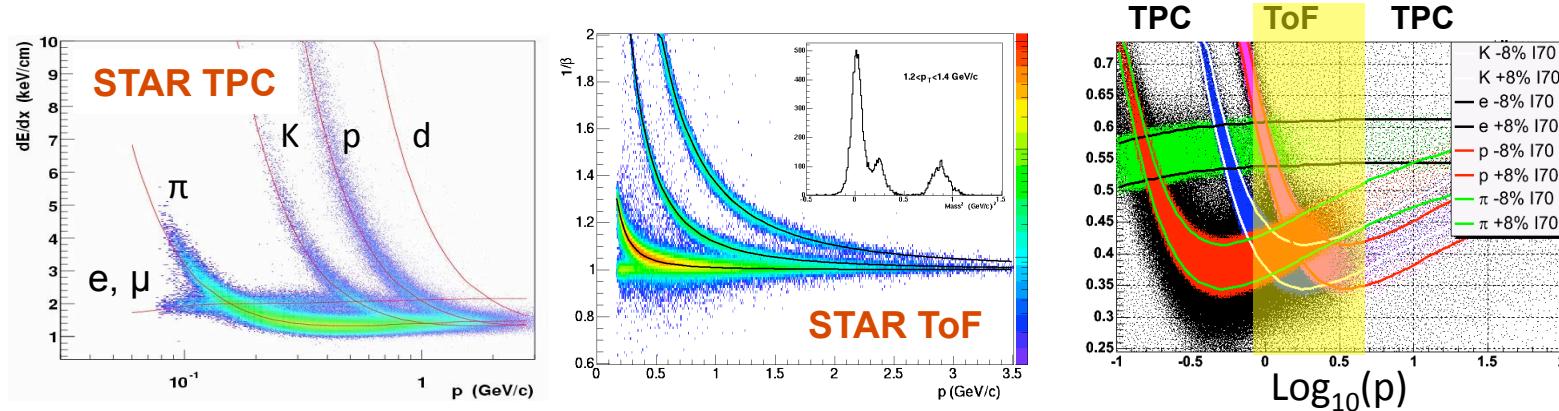




# STAR Detectors: Full $2\pi$ particle identification!



# Particle Identification at STAR



**Neutral particles**

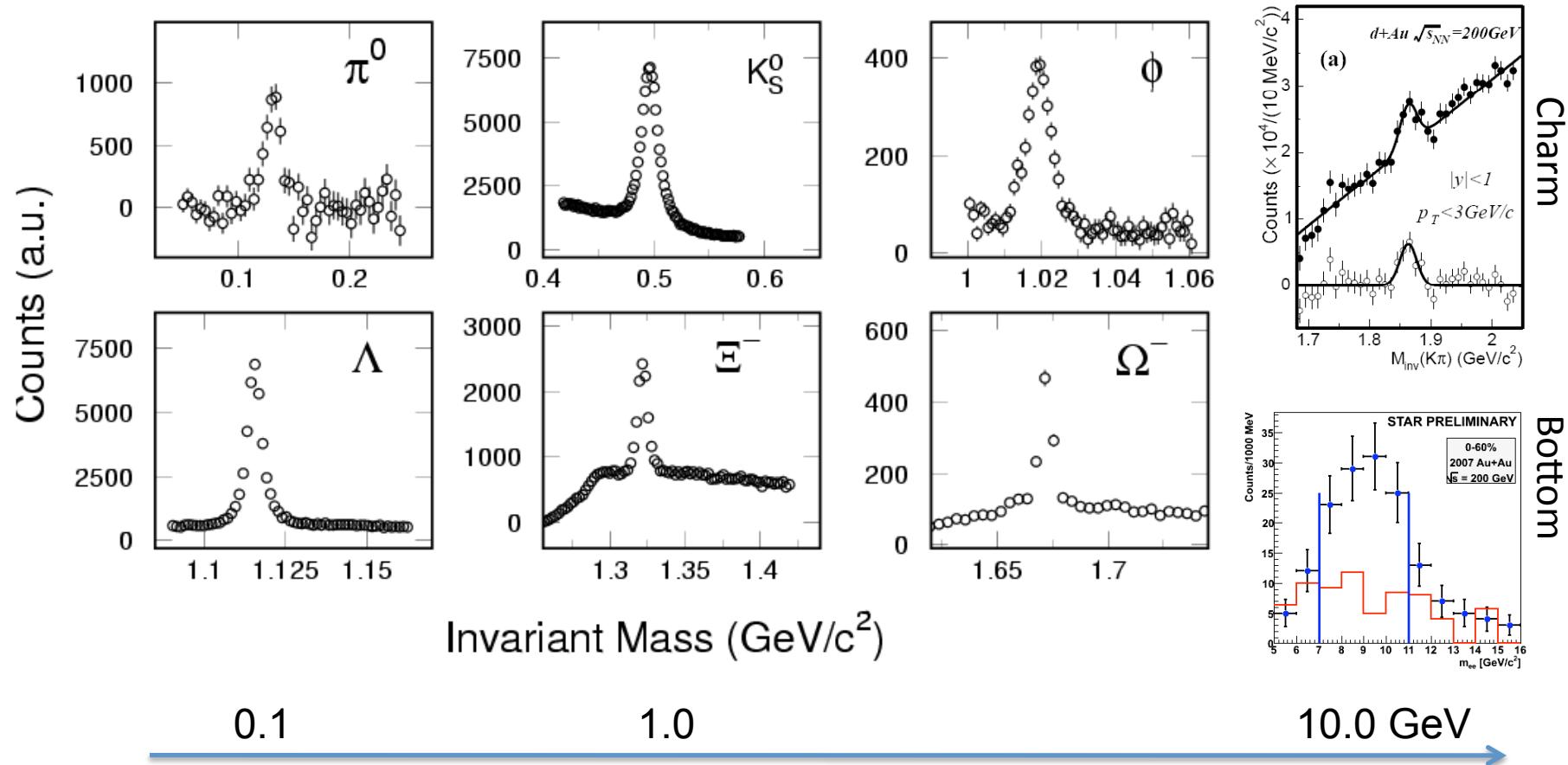
**Strange hyperons**

**Jets**

**Heavy Quark Hadrons**

***Multiple-fold correlations among the identified particles!***

# Particle Identification (ii)

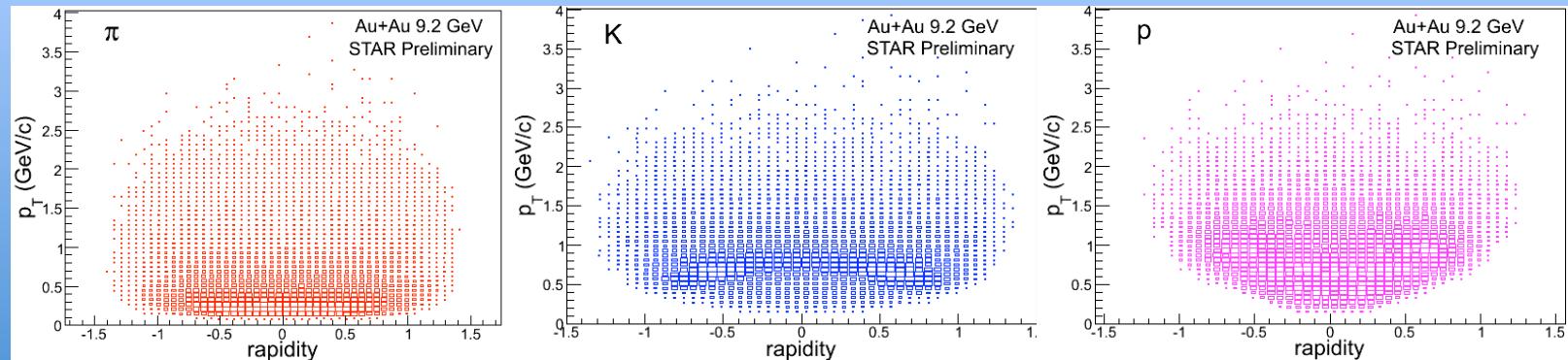


Reconstruct particles in full azimuthal acceptance of STAR!

# Collider Acceptance

Collider Mode STAR

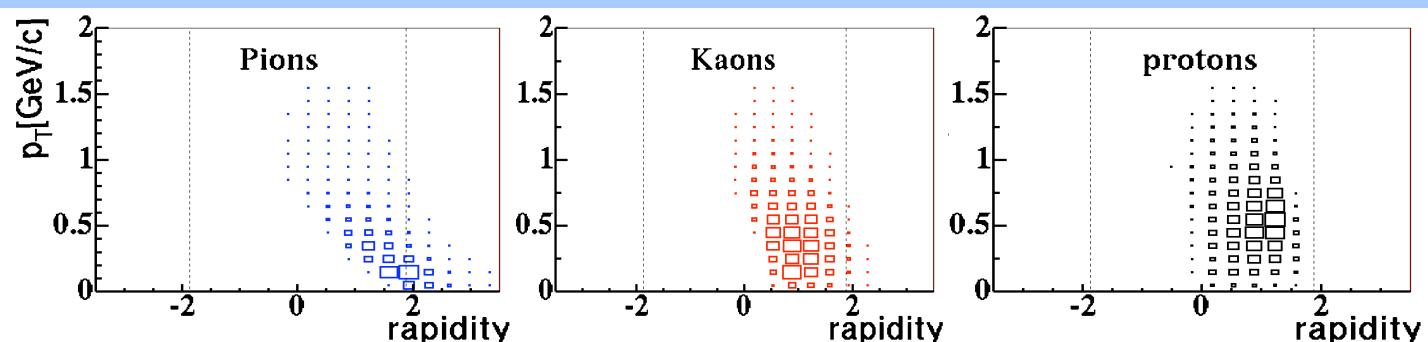
$\sqrt{s_{NN}} = 9.2 \text{ GeV Au+Au Collisions at RHIC}$



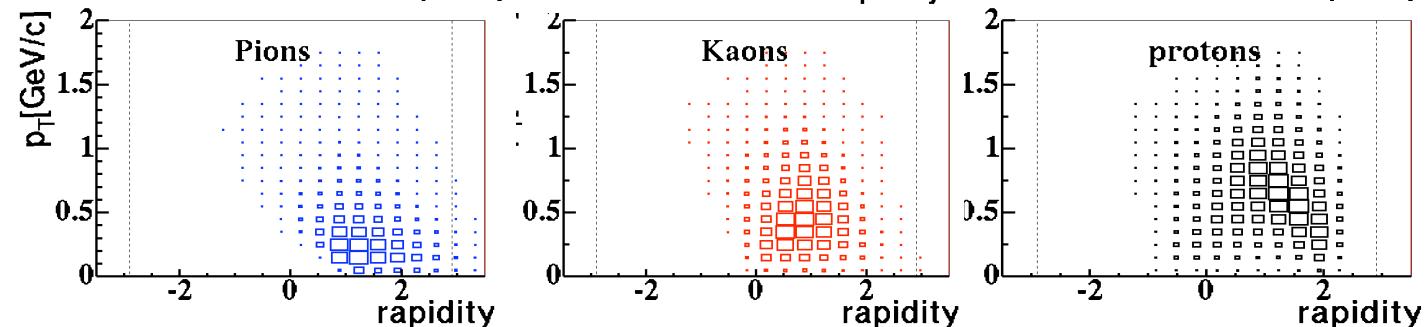
Fix-target Mode NA49

$\sqrt{s_{NN}}$

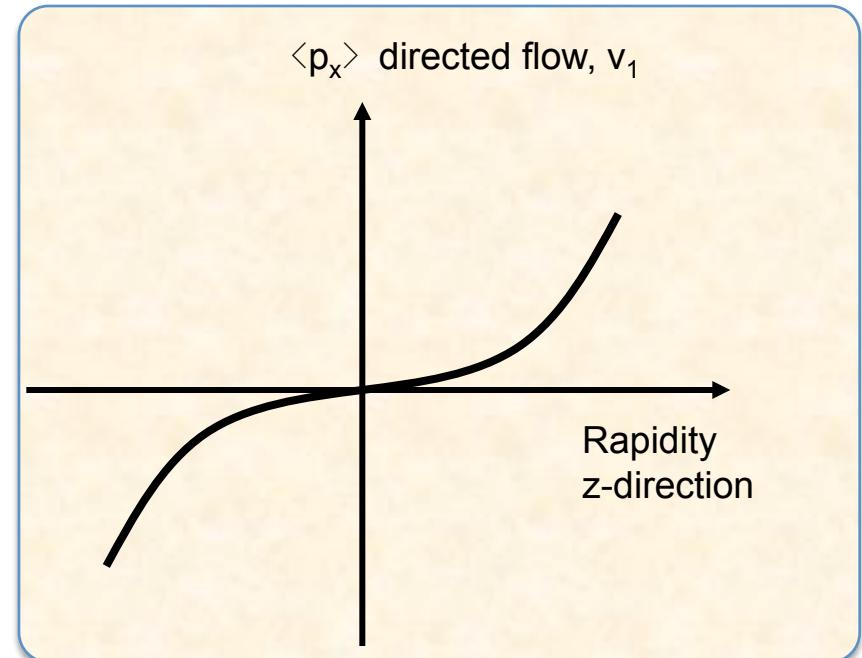
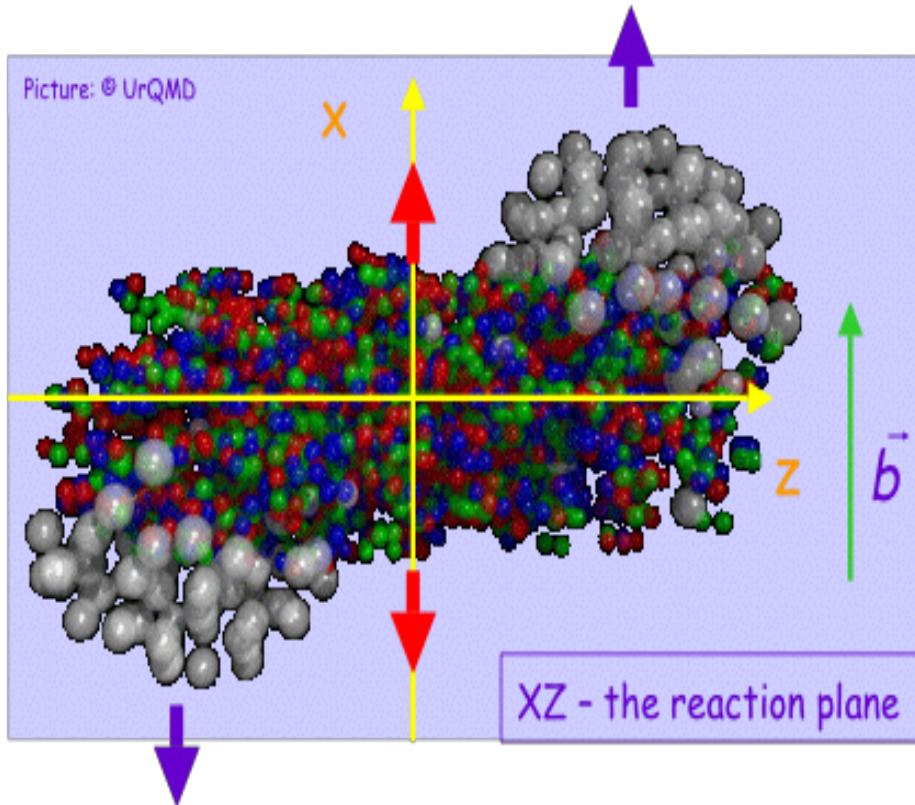
6 GeV



17 GeV



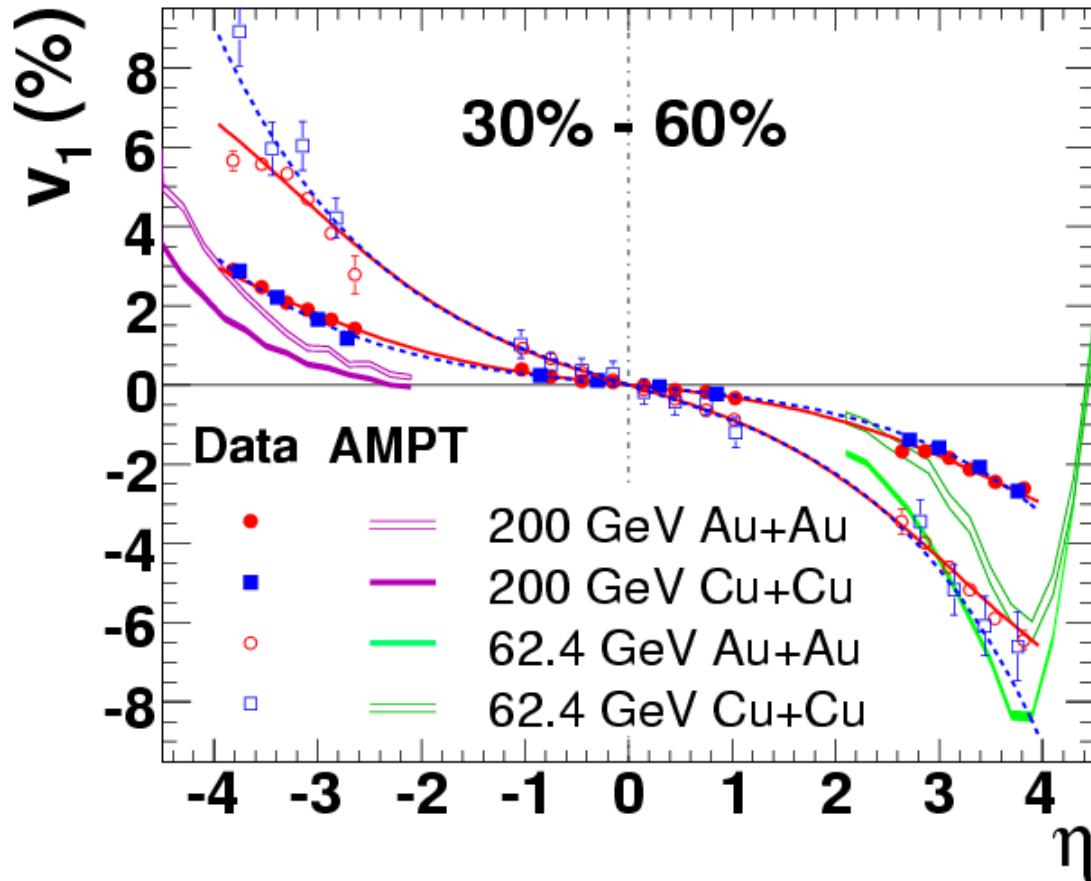
# Direct Flow $v_1$



$$E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_t dp_t dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \psi_r)] \right)$$

$$v_n = \langle \cos[n(\varphi - \psi_r)] \rangle$$

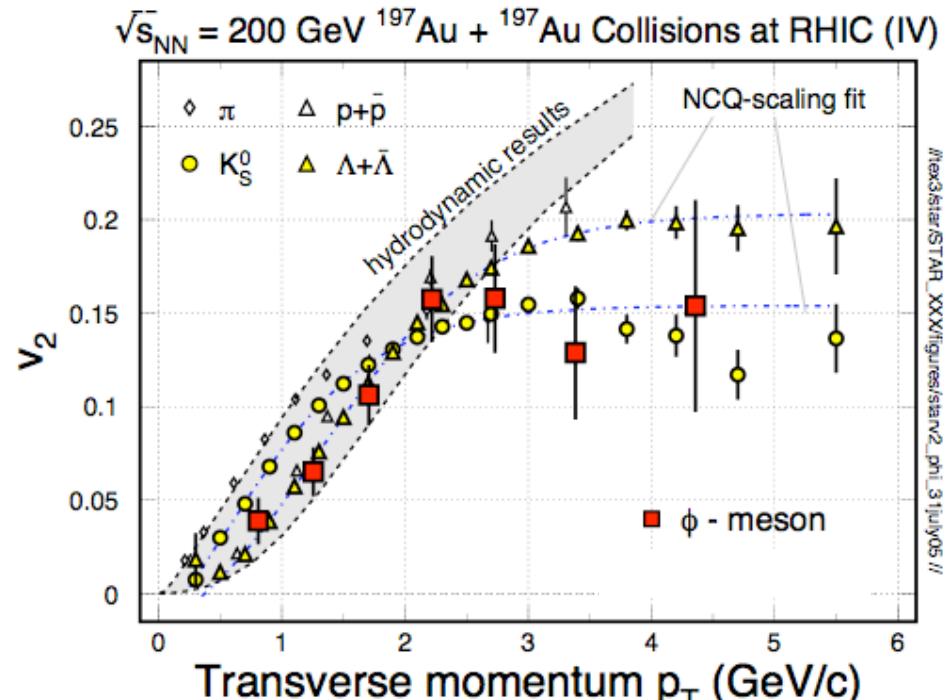
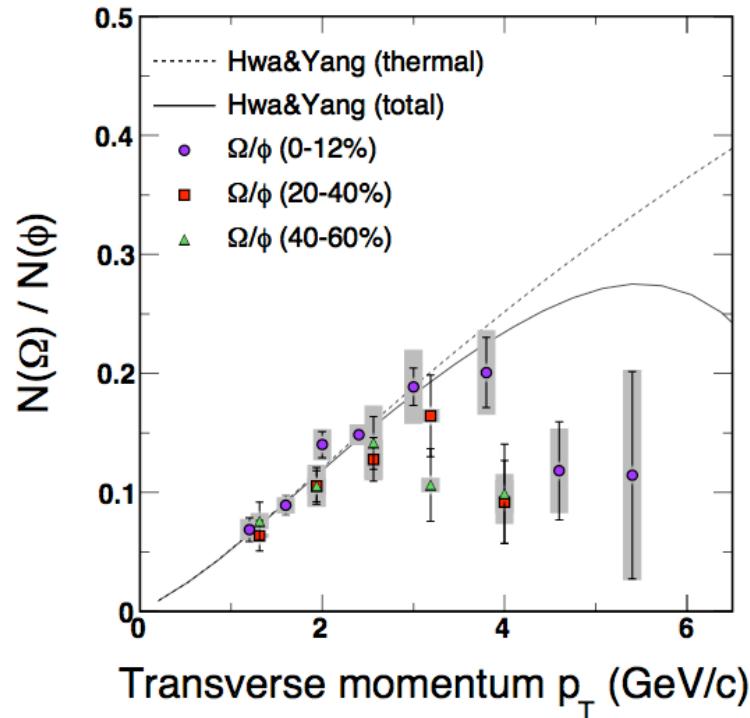
# $v_1(\eta)$ : System-size Dependence



- Energy dependent but weak system size dependence observed.
- Model calculations do not work at forward region.

STAR: 0807.1518, PRL in print

# $\phi$ -meson Flow: Partonic Flow



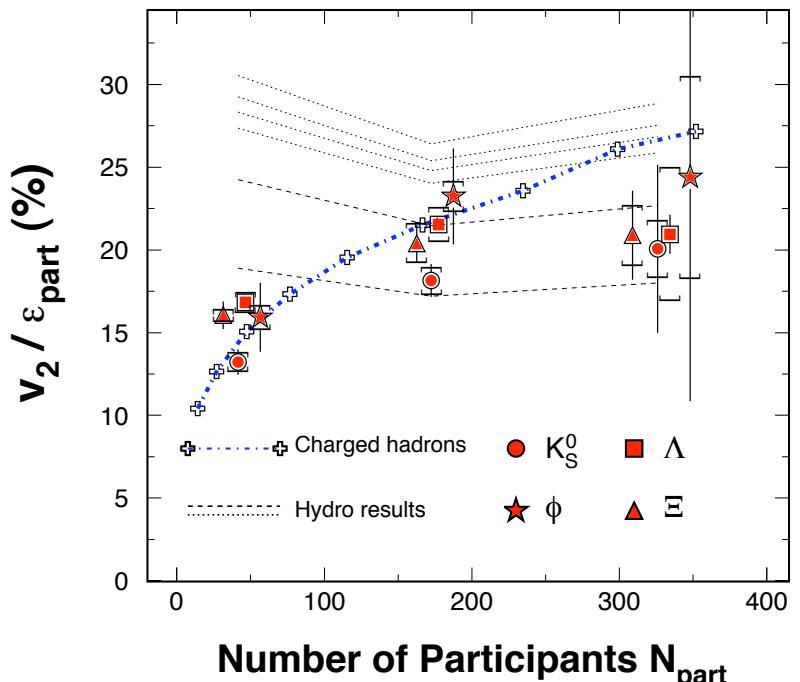
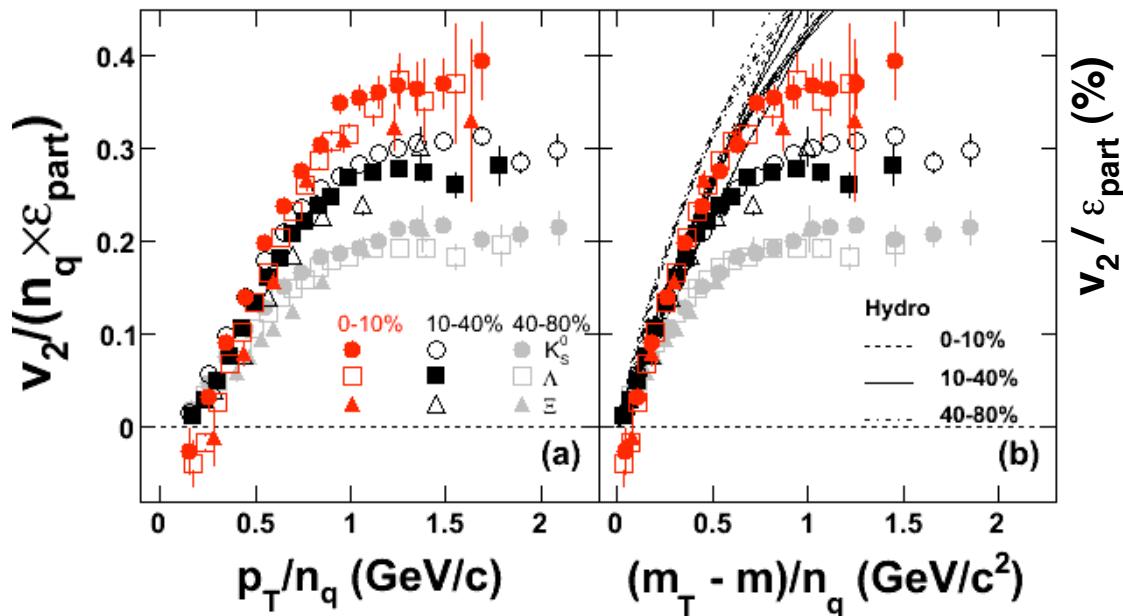
**" $\phi$ -mesons are produced via coalescence of seemingly thermalized quarks in central Au+Au collisions. This observation implies **hot and dense matter with partonic collectivity** has been formed at RHIC"**

STAR: Phys. Rev. Lett. **99** (2007) 112301// \* STAR, Duke, TAMU

# Centrality Dependence $v_2$

STAR: Phys. Rev. **C77**, 54901(2008)

**200 GeV Au+Au**



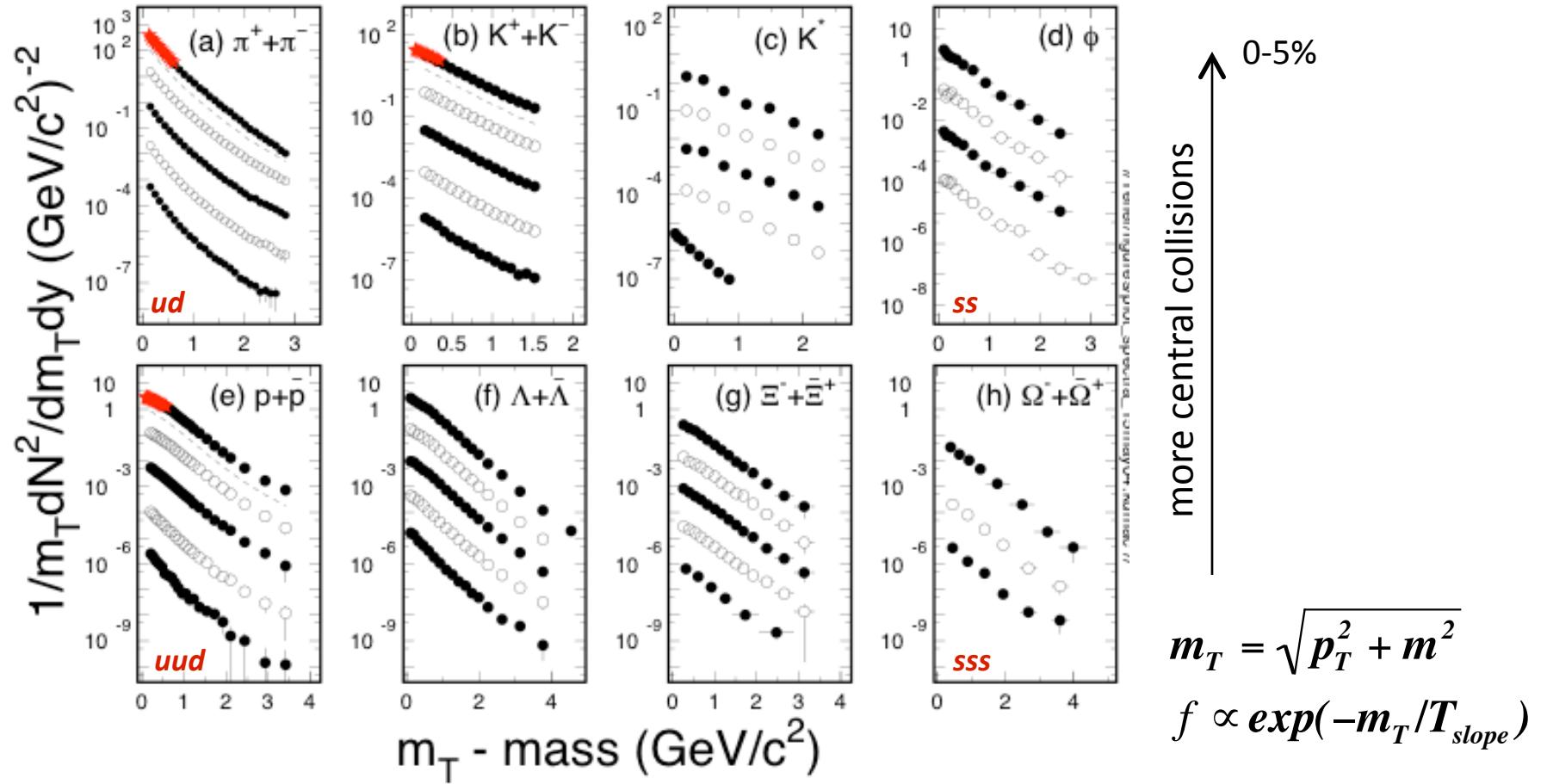
S. Voloshin, A. Poskanzer, PL **B474**, 27(00).

D. Teaney, et. al., nucl-th/0110037

- Larger  $v_2/\epsilon_{\text{part}}$  indicates stronger flow in more central collisions.
- NO  $\epsilon_{\text{part}}$  scaling.
- The observed  $n_q$ -scaling does not necessarily mean thermalization.

# Hadron Spectra from RHIC

*p+p and Au+Au collisions at 200 GeV*

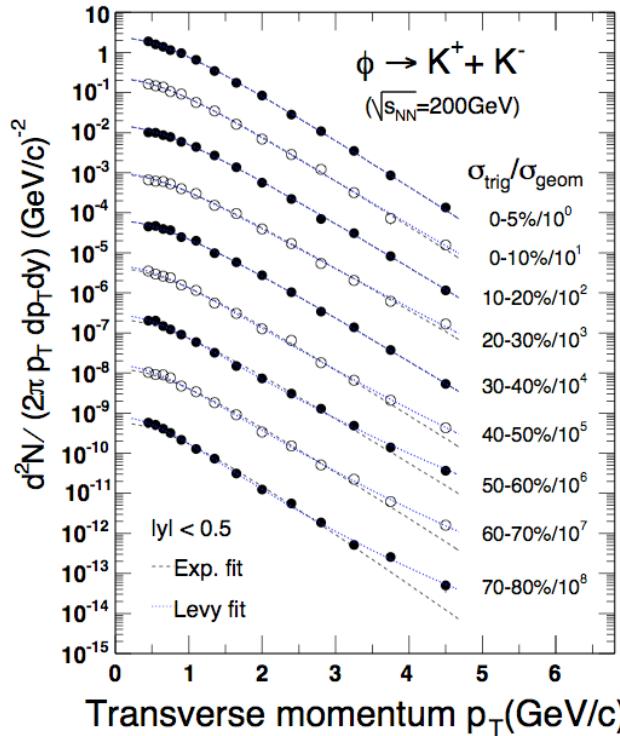


**Multi-strange hadron spectra are exponential in shape.**

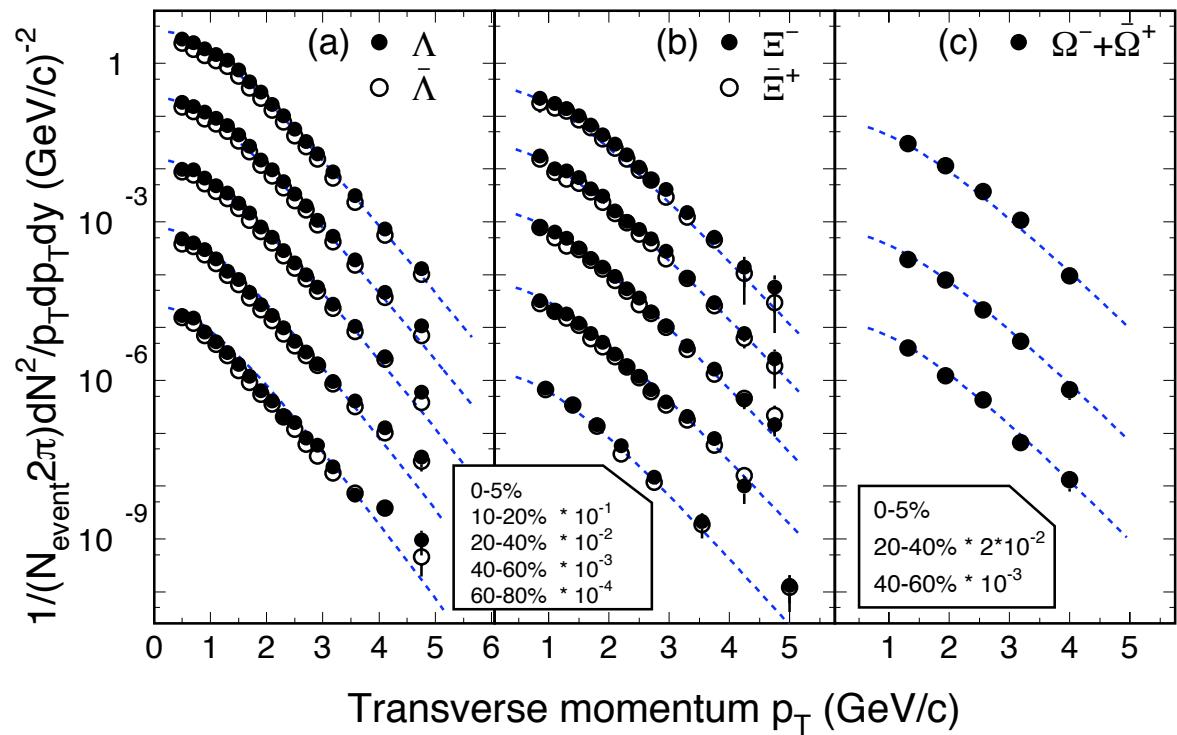
STAR white papers - Nucl. Phys. A757, 102(2005).

# $\phi$ - mesons and Strange Baryons

STAR: PRL. **99** (2007) 112301



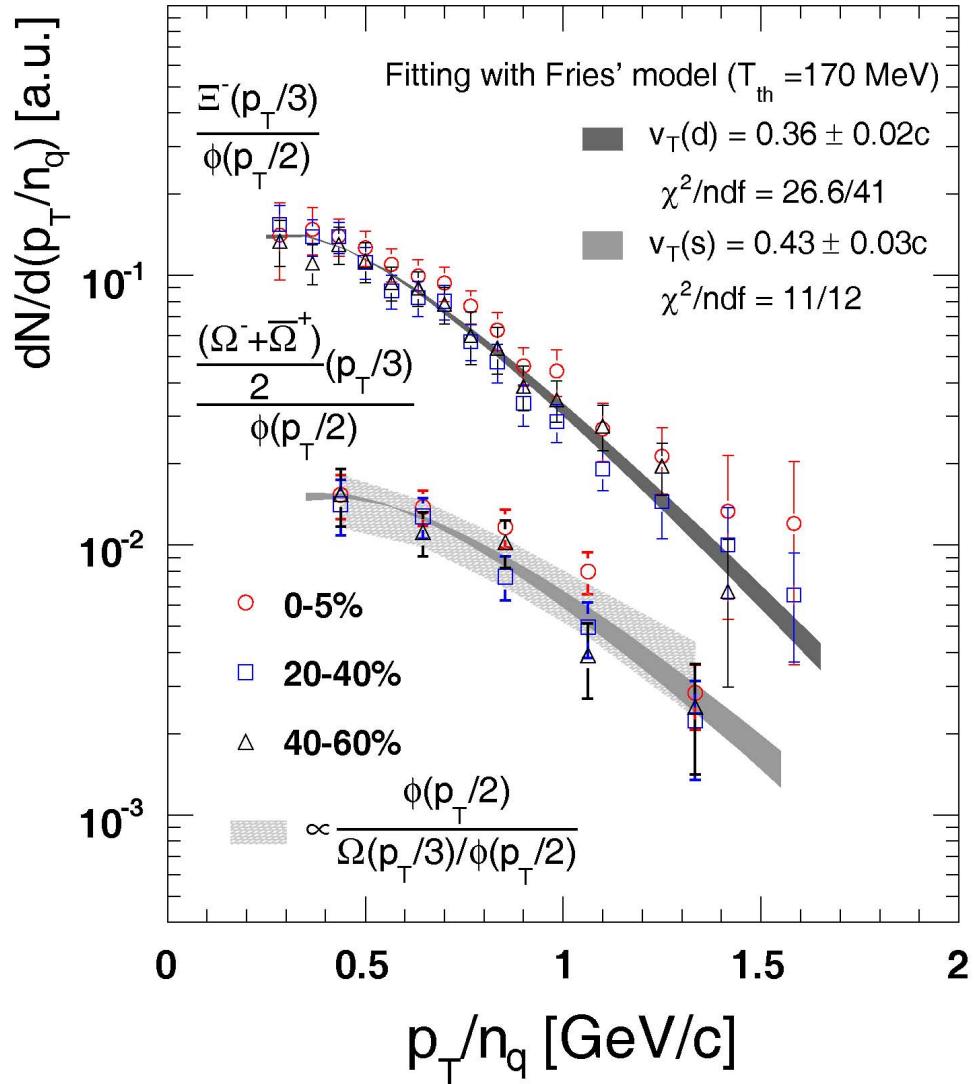
Phys. Rev. Lett. **98**, 62301(2007)



ssbar fusion  $\Rightarrow$   $\phi$ -meson formation!

STAR: Phys. Lett. **B612**, 81(2005)

# The *s*- and *d*-quark Spectra



$$S = \frac{\Omega(p_T/3)}{\phi(p_T/2)}$$

$$d = \frac{\Xi(p_T/3)}{\phi(p_T/2)}$$

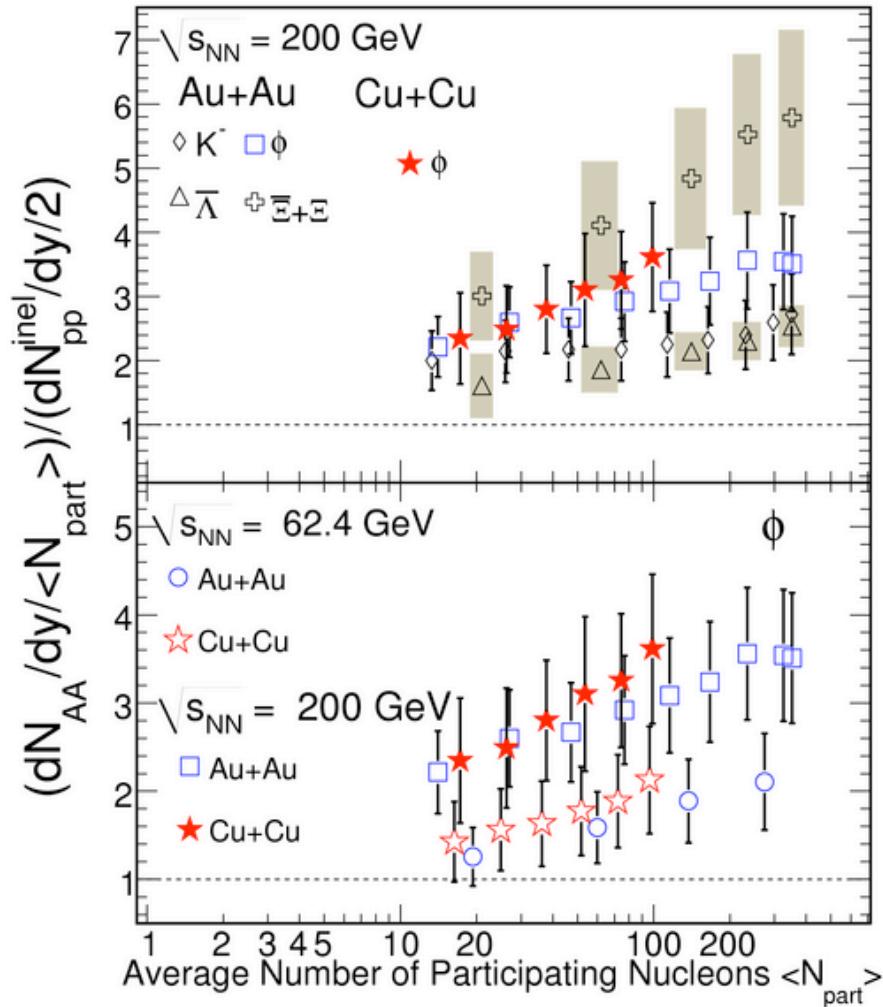
Assuming that the process of hadronization follows coalescence  
 →

- parton spectra
- ‘partonic collective flow’
- velocity  $\sim 0.35\text{--}0.45 c$

JinHui Chen: SQM08  
 c.f. Phys. Rev. C78 (2008) 034907

# Strangeness Enhancement - $\phi$

STAR: arXiv 0810.4979



## 200 GeV collisions

- The multi-strange baryons productions  $\Xi, \Omega$  are enhanced in heavy ion collisions compared to that of in p+p collisions

- The  $\phi$ -meson productions are also enhanced, but may be with different trends



The (strangeness) enhancement is NOT due to CE suppression!

STAR:

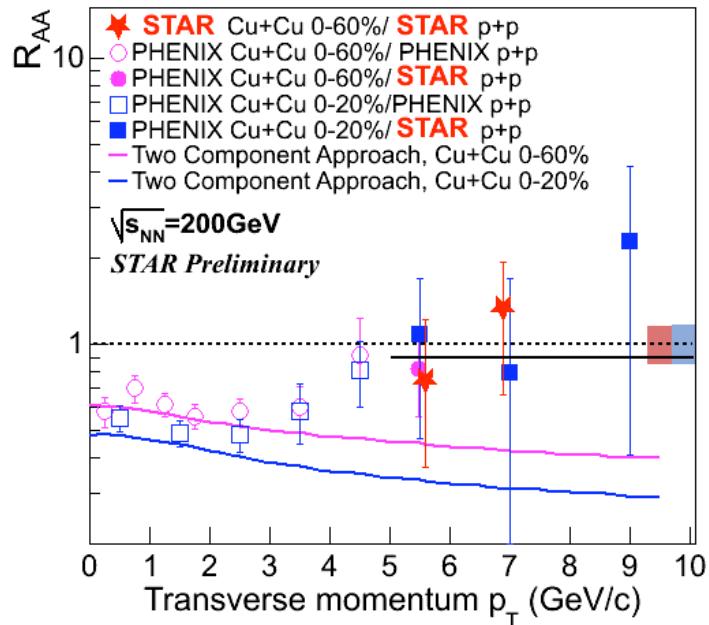
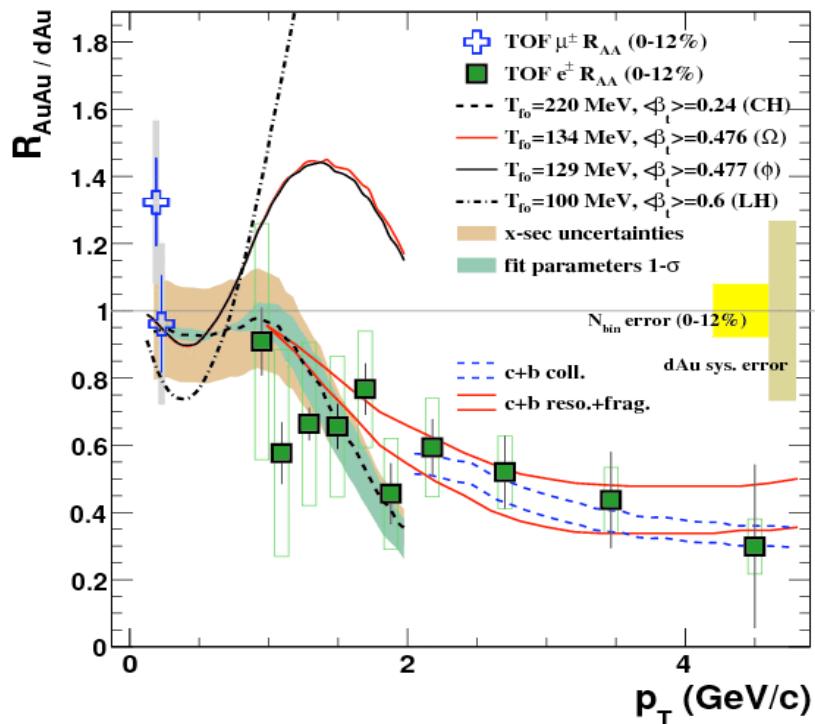
*Sub. to Phys Lett. B, 2008*

- *PRL.* **98** (2007) 062301 (*nucl-ex/0606014*)
- *nucl-ex/0703033*
- *nucl-ex/0705.2511*

# Open Charm and J/ $\psi$ R<sub>AA</sub>(p<sub>T</sub>)

STAR: sub. to PRL, arXiv: 0805.0364

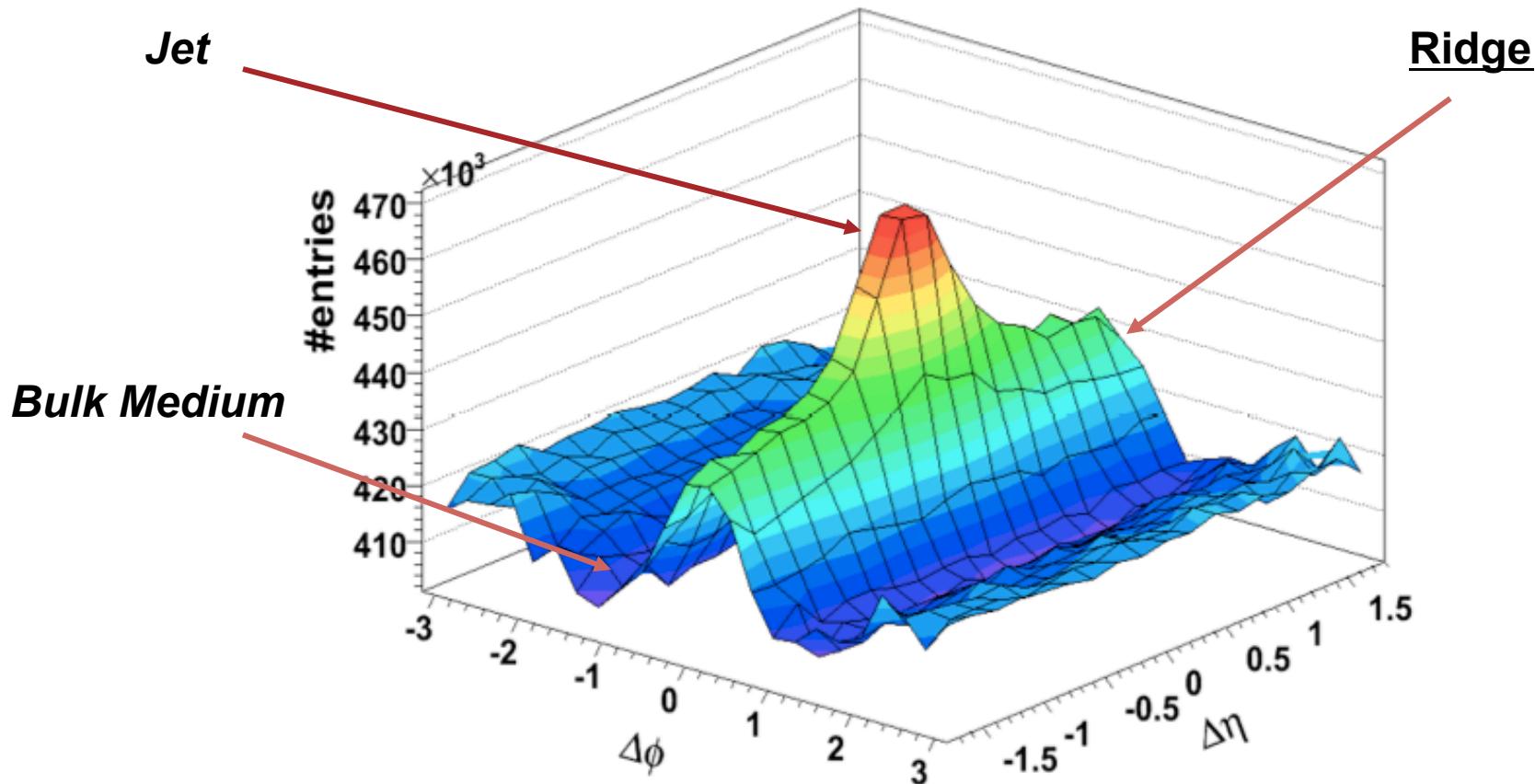
Heavy flavor hadrons freeze-out earlier than light flavor (u,d,s) hadrons



STAR Preliminary:

- The Cu+Cu data consistent with no suppression at high p<sub>T</sub>:
- $R_{AA}(p_T > 5 \text{ GeV}/c) = 0.9 \pm 0.2$
- Low-p<sub>T</sub> R<sub>AA</sub>  $\sim 0.5\text{-}0.6$  (PHENIX)
- Most models expect R<sub>AA</sub> to decrease at high p<sub>T</sub>.

# The Ridge from RHIC

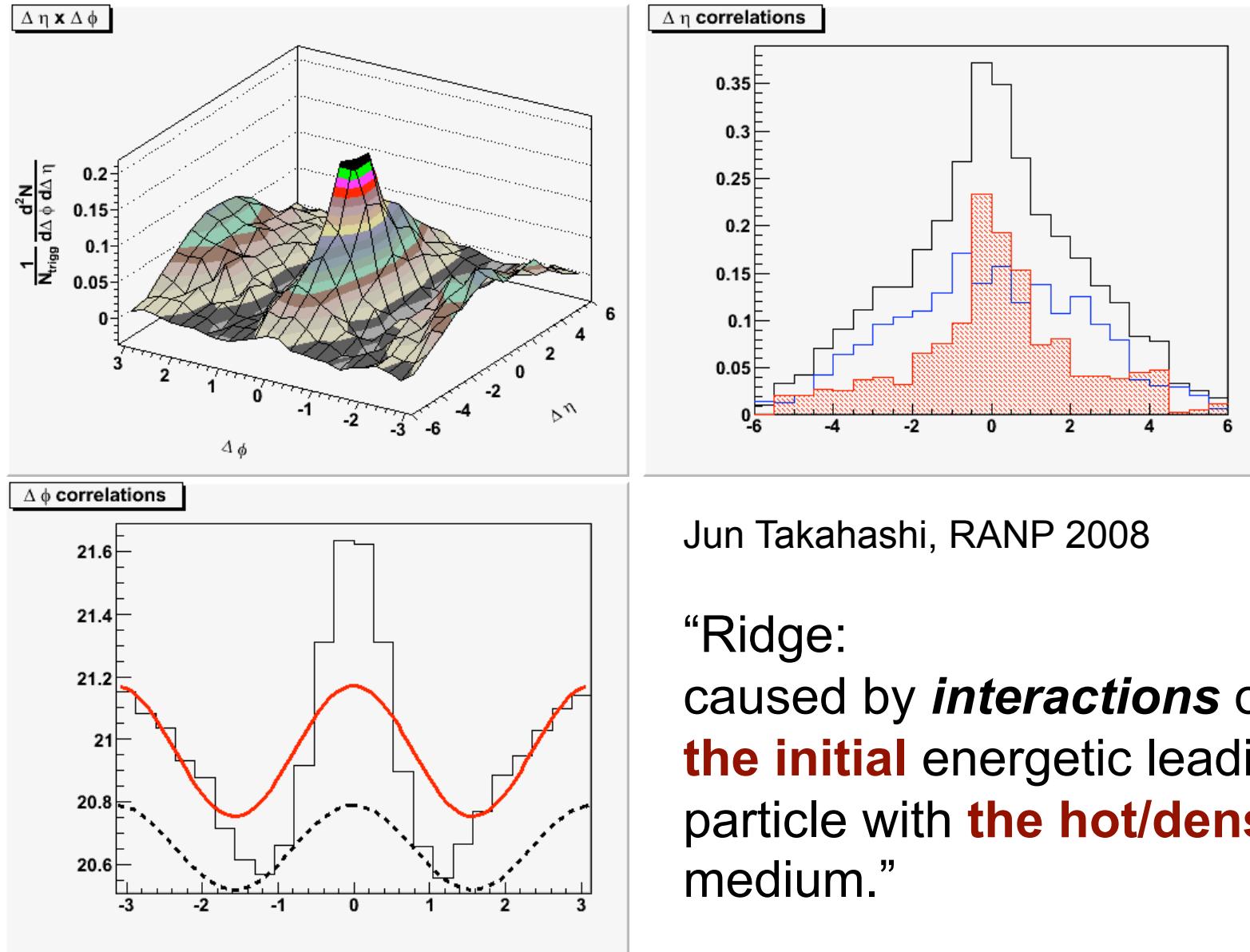


STAR: J.Putschke, J.Phys.**G34**:S679 (07)

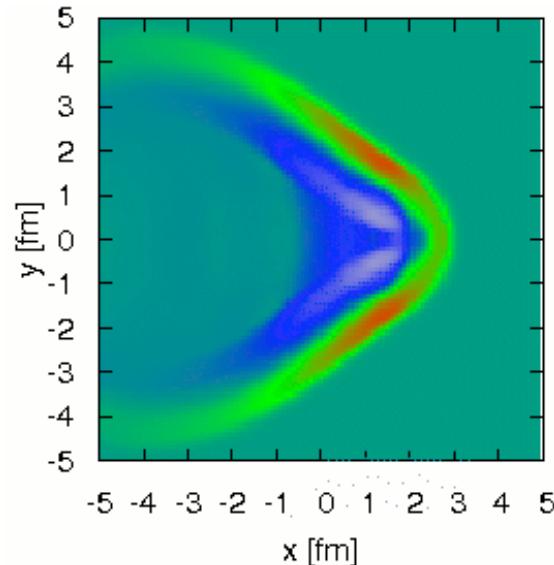
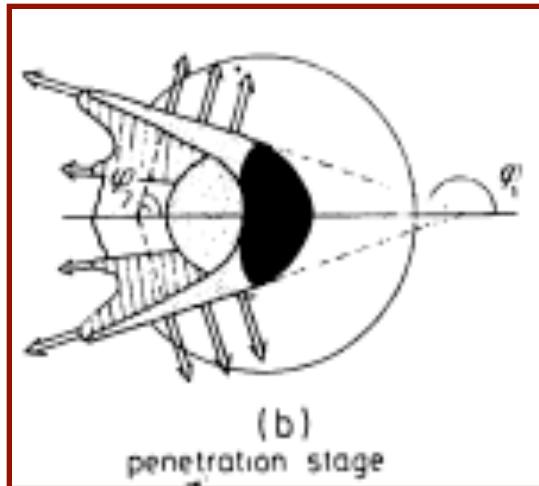
Rich underlying physics: initial condition, jet, bulk, *jet-medium interaction\**, medium responses,...

*N. Armesto et al.; R. Hwa; T. Kodama\*, A. Majumder, et al.; E. Suryak; S. Voloshin; C.Y. Wong*

# Ridge: NEXUS + Hydro



# Mach-Cone

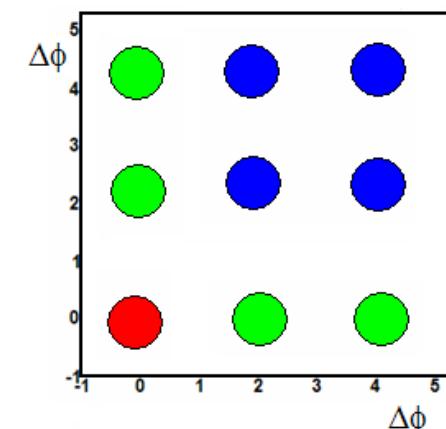
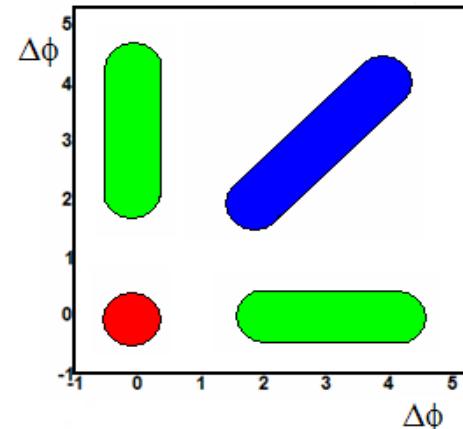
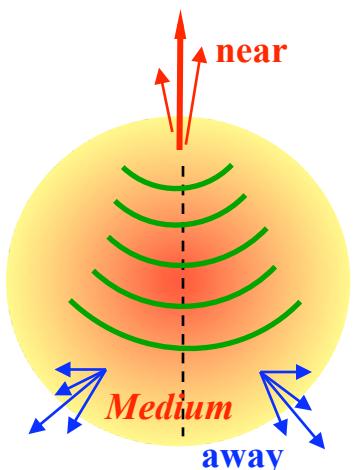
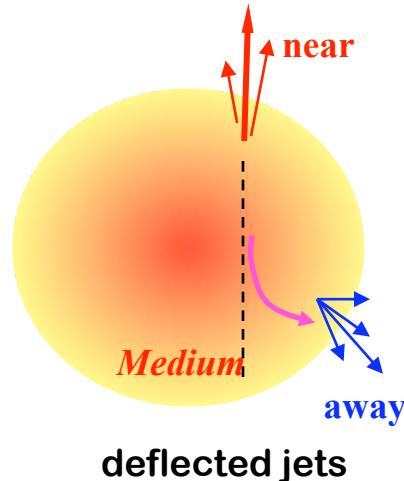


- **Mach shock waves:** J. Hofmann, H. Stocker, U. Heinz, W. Scheid, W. Greiner  
Phys. Rev. Lett., 36, (76)
- In high-energy nuclear collisions, a useful tool to analyze the interaction between energetic jets and hot/dense medium in order to extract the properties of the medium.
- **Model predictions:** hydrodynamic, QCD, transport, Ads/CFT

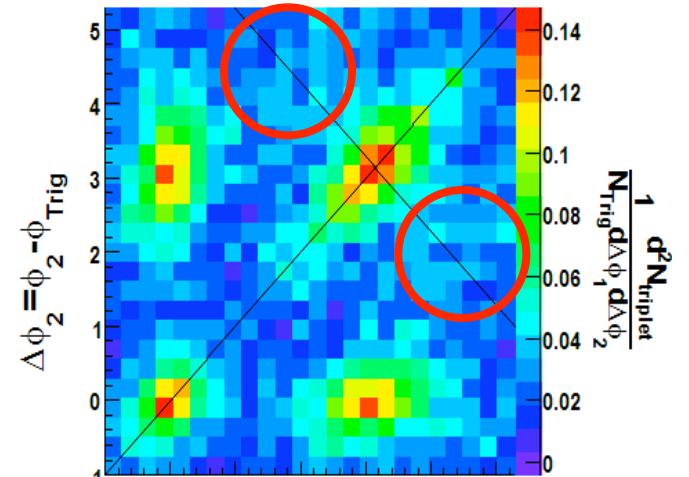
# Search for Mach Cone

with Three Particle Correlations

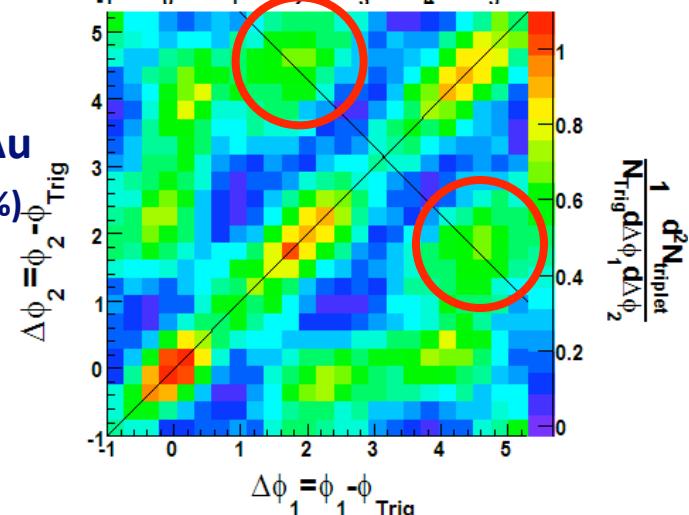
STAR: sub. to PRL, arXiv: 0805.0622



$d+Au$



$Au+Au$   
(0-12%)



$$\cos \vartheta^{Mach} = \sqrt{p/\varepsilon}$$

**"Evidence of conical emission ..."**



# sQGP and the QCD Phase Diagram

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In 200 GeV Au+Au collisions at RHIC, strongly interacting matter formed:

- Jet energy loss:  $R_{AA}$
- Strong collectivity:  $v_0, v_1, v_2$
- Hadronization via coalescence:  $n_q$ -scaling

## Questions:

*Is thermalization reached at RHIC?*

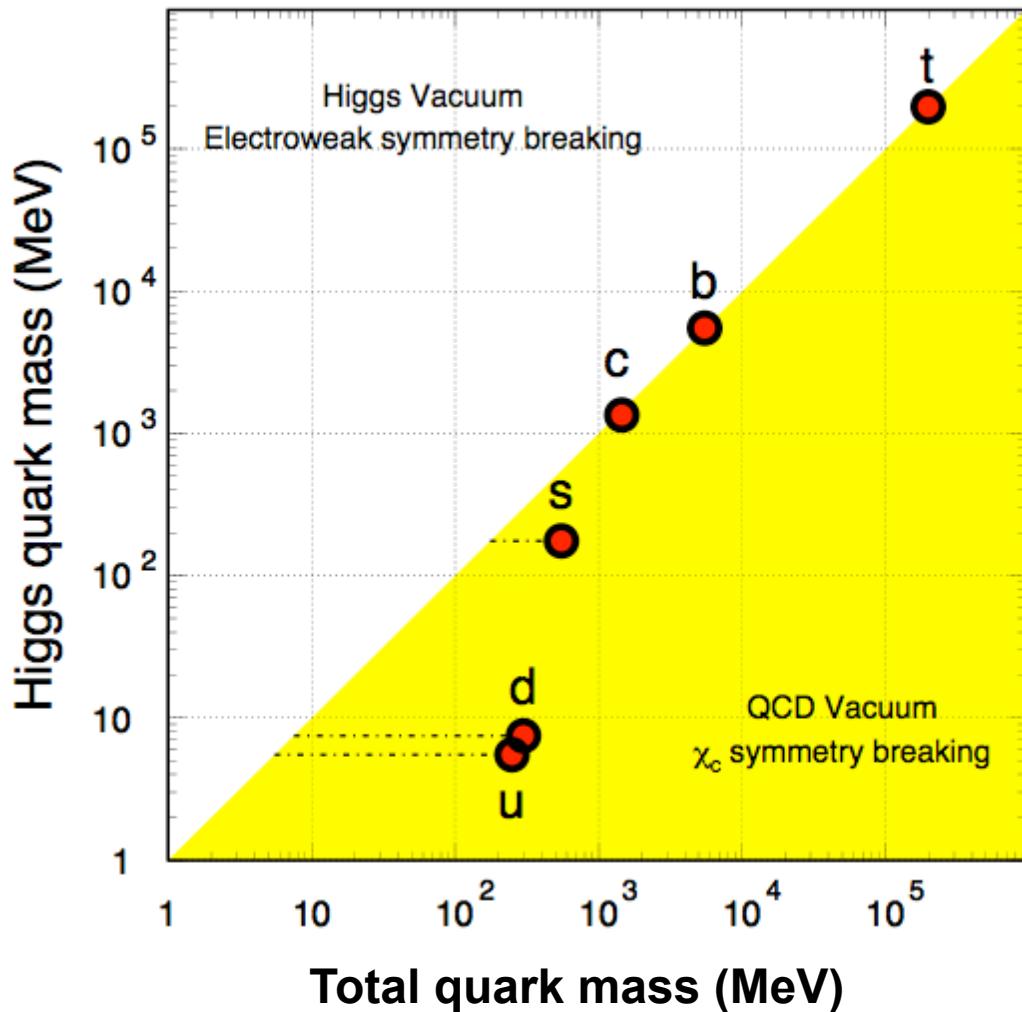
- Systematic analysis with  $dN/dp_T$  and  $dv_2/dp_T$  results...
- Heavy quark measurements

*When (at which energy) does this transition happen?*

*What does the QCD phase diagram look like?*

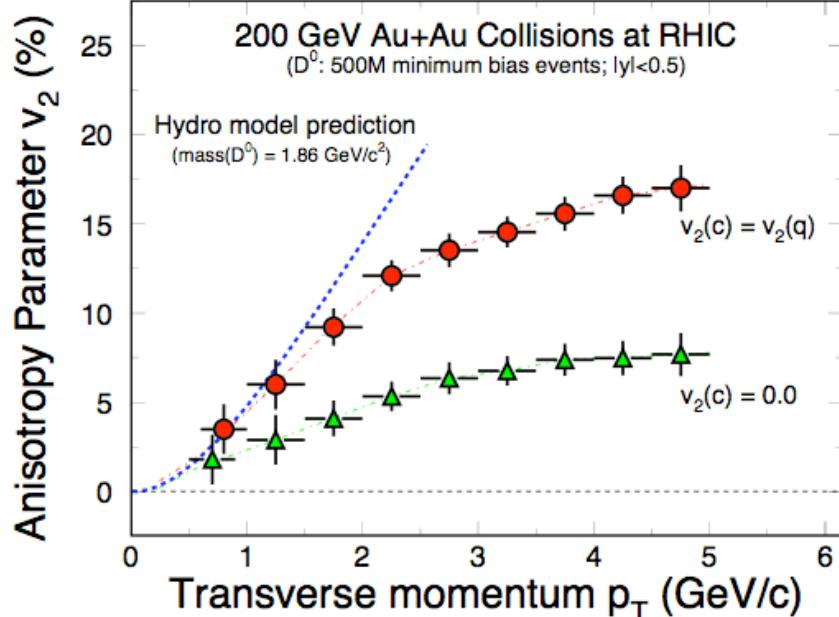
- RHIC Beam Energy Scan / (CBM)

# Quark Masses



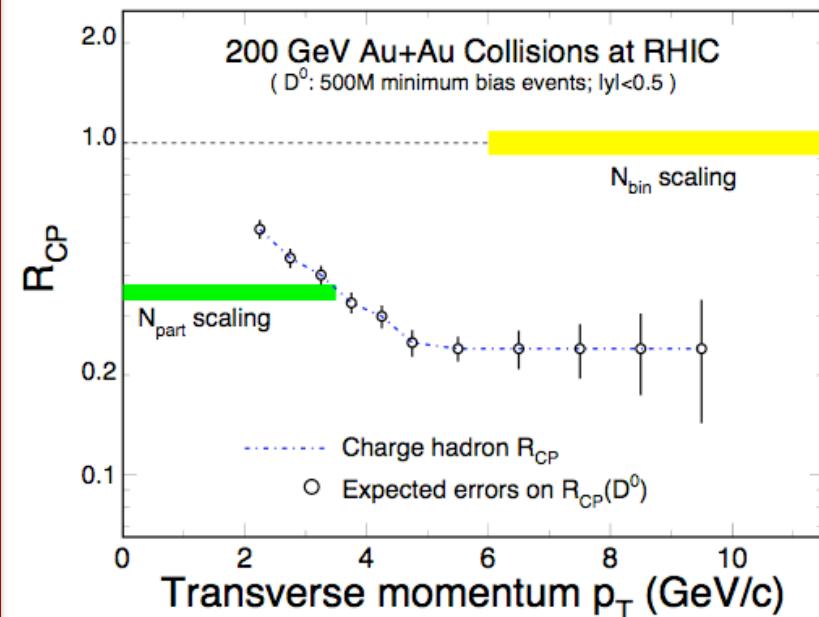
- 1) Higgs mass: electro-weak symmetry breaking. (current quark mass)
  - 2) QCD mass: Chiral symmetry breaking. (constituent quark mass)
- ⇒ New mass scale compared to the excitation of the system.
  - ⇒ Important tool for studying properties of the hot/dense medium at RHIC.
  - ⇒ Test pQCD predictions at RHIC.

# Charm Hadron $v_2$ and $R_{AA}$



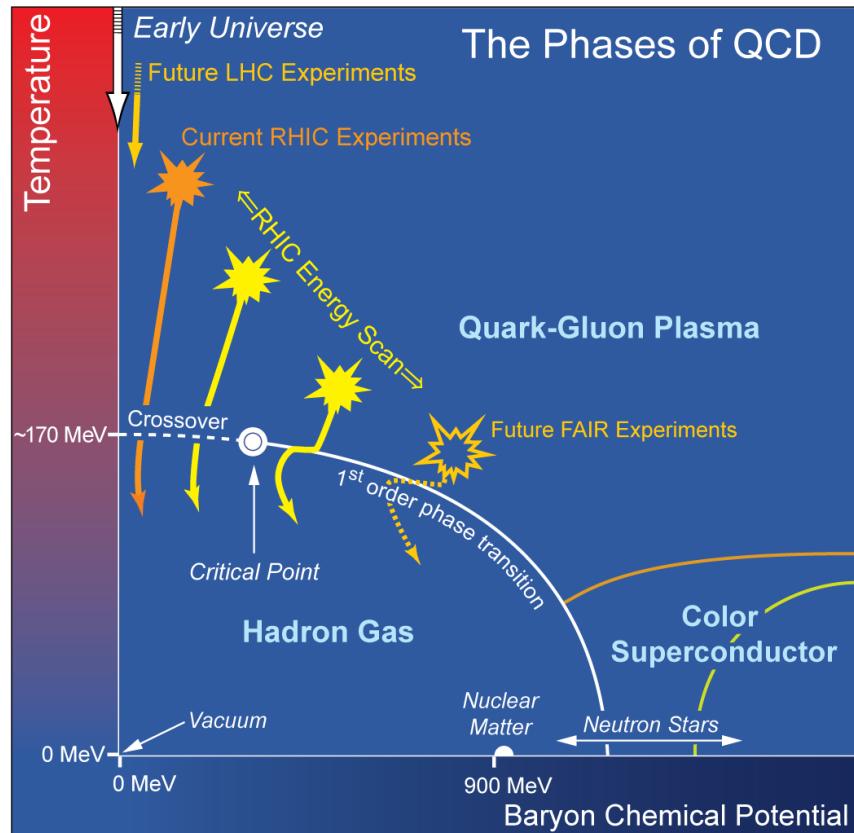
- 200 GeV Au+Au m.b. collisions (500M events).
- Charm hadron collectivity  $\Rightarrow$  drag/diffusion constants  $\Rightarrow$

**Medium properties!**



- 200 GeV Au+Au m.b. collisions ( $|y|<0.5$  500M events)
- Charm hadron  $R_{AA} \Rightarrow$
- Energy loss mechanism!
- QCD in dense medium!

# The QCD Phase Diagram



**STAR's plan:**

**run10: RHIC Beam Energy Scan**

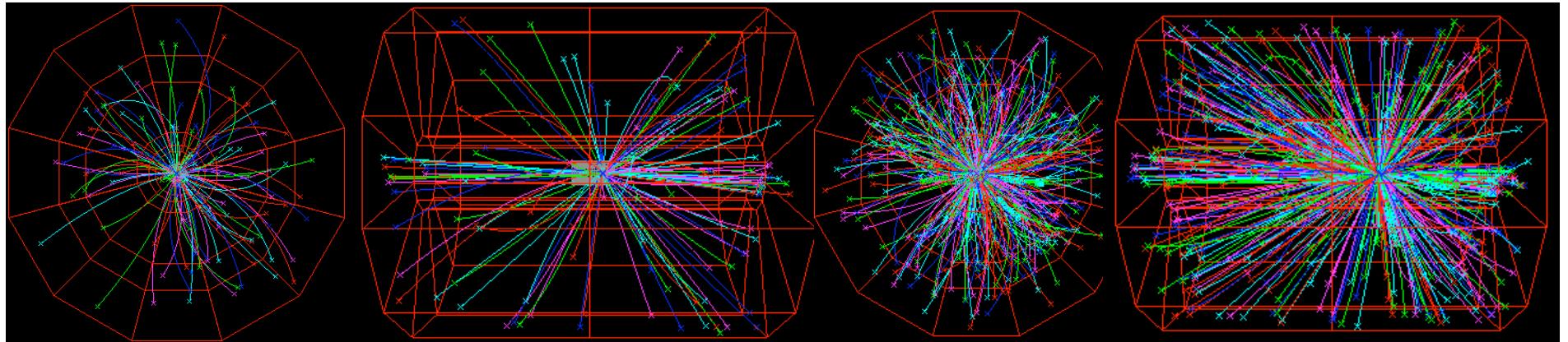
**run11: Heavy Quark measurements**

- LGT prediction on the transition temperature,  $T_c \sim 170$  MeV.
- LGT calculation, universality, and models point to the existence of the critical point on the QCD phase diagram\* at finite baryon chemical potential.
- Experimental evidence for either the critical point or 1<sup>st</sup> order transition is important for our knowledge of the QCD phase diagram\*.

\* Thermalization is assumed

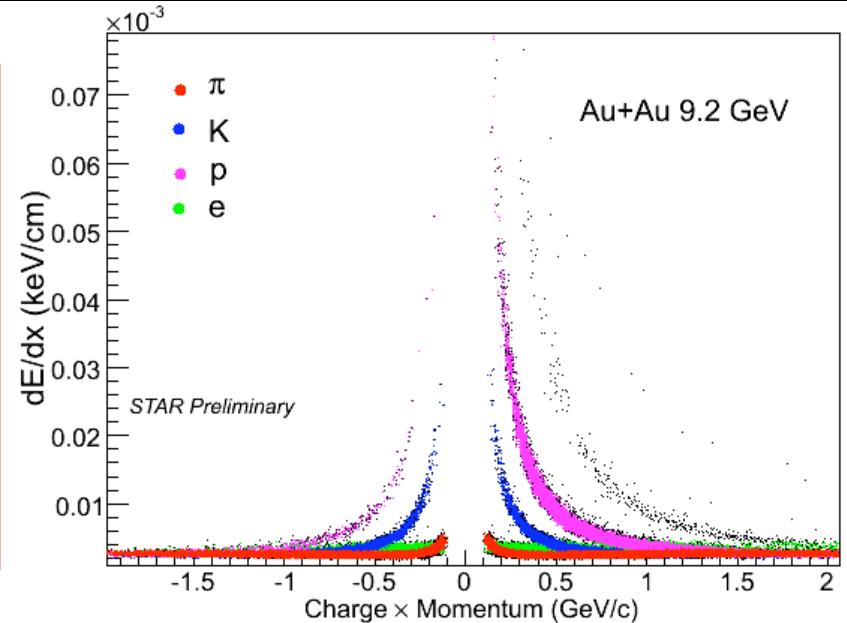
Stephanov, Rajagopal, and Shuryak, *PRL* **81**, 4816(98)  
 Rajagopal, *PR D61*, 105017 (00)  
<http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf>

# Au + Au Collisions at 9.2 GeV



- 1) ~ 3500 collisions collected
- 2) Determine Luminosity
- 3) STAR has preliminary results on:

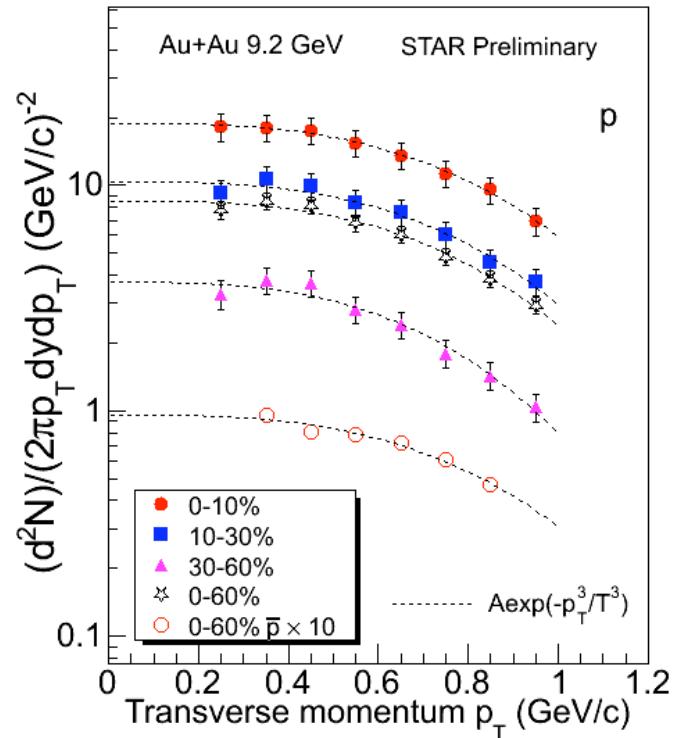
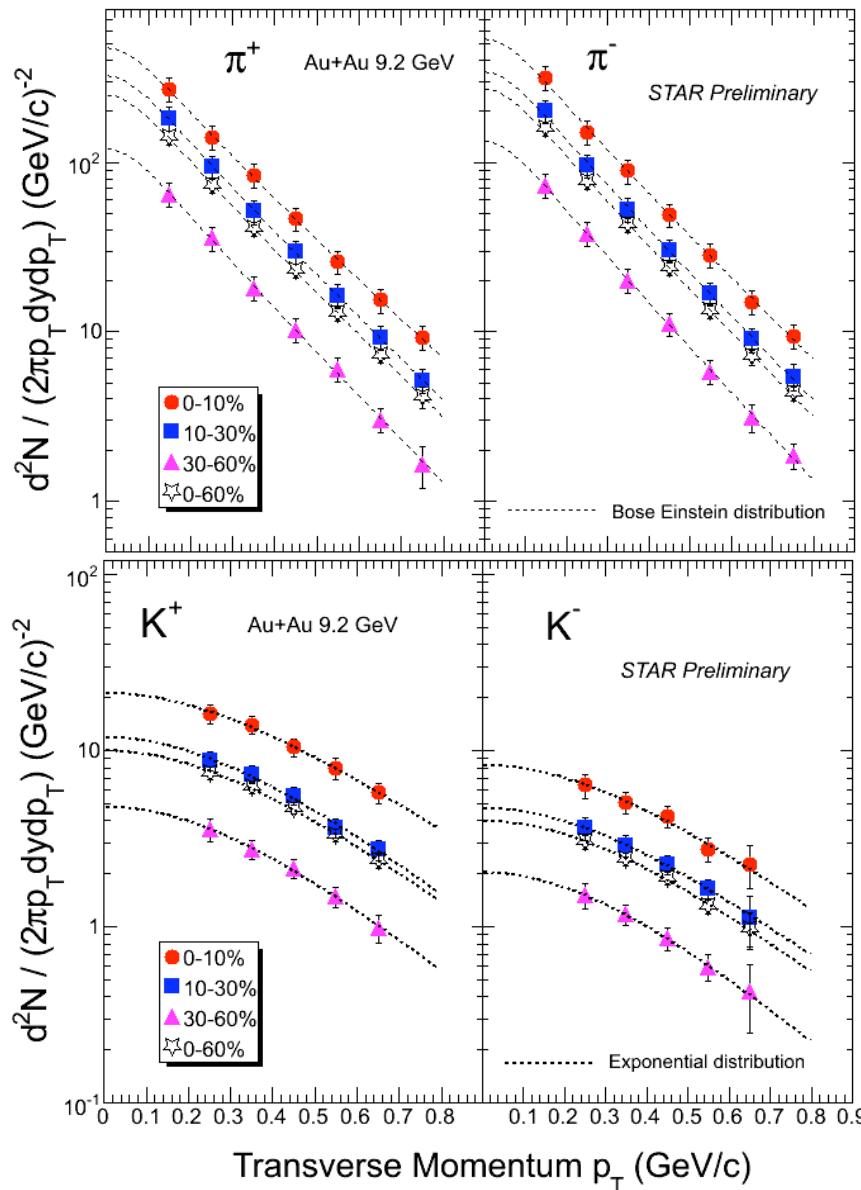
Particle identification in TPC; charged multiplicity,  $\pi$ - $\pi$  interferometry, particle spectra and ratios;  $v_1$  and  $v_2$



PID will be further significantly extended using full TOF.

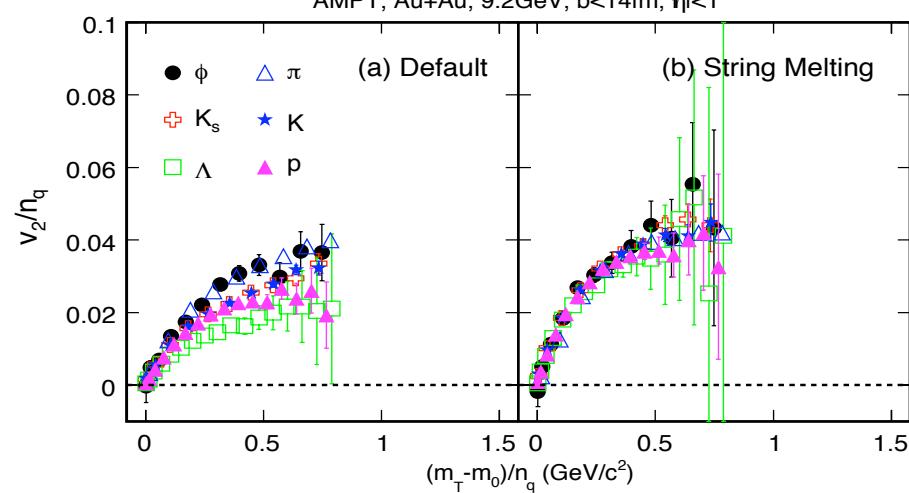
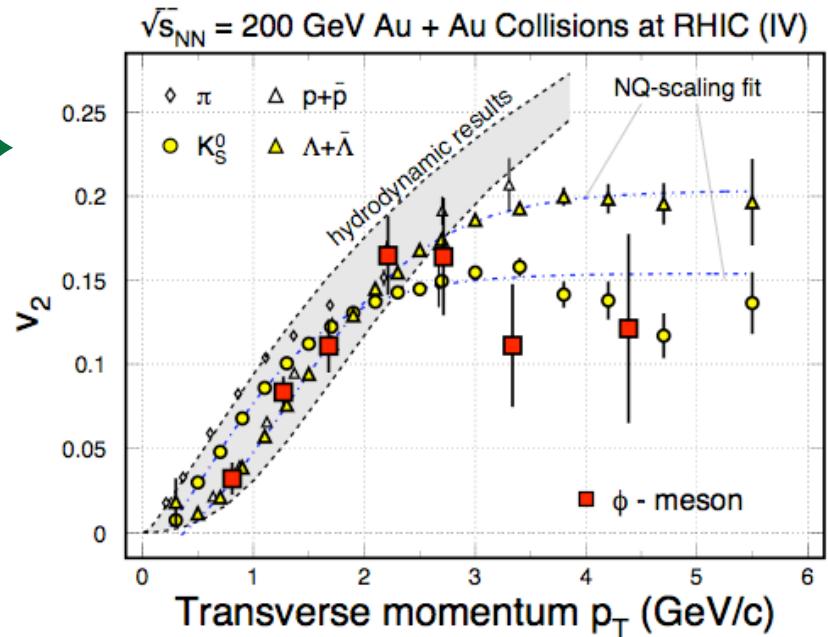
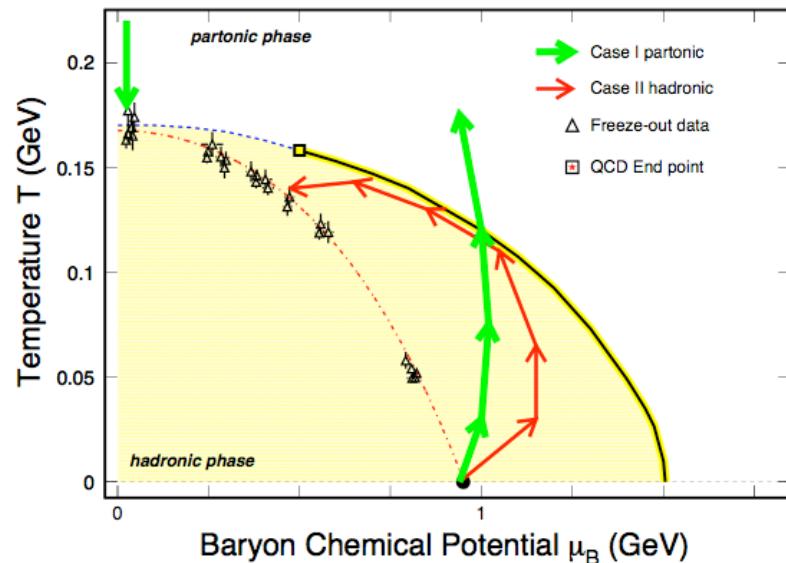
Lokesh SQM08

# Identified Hadron Spectra at mid-y



Lokesh Kumar  
STAR: SQM2008

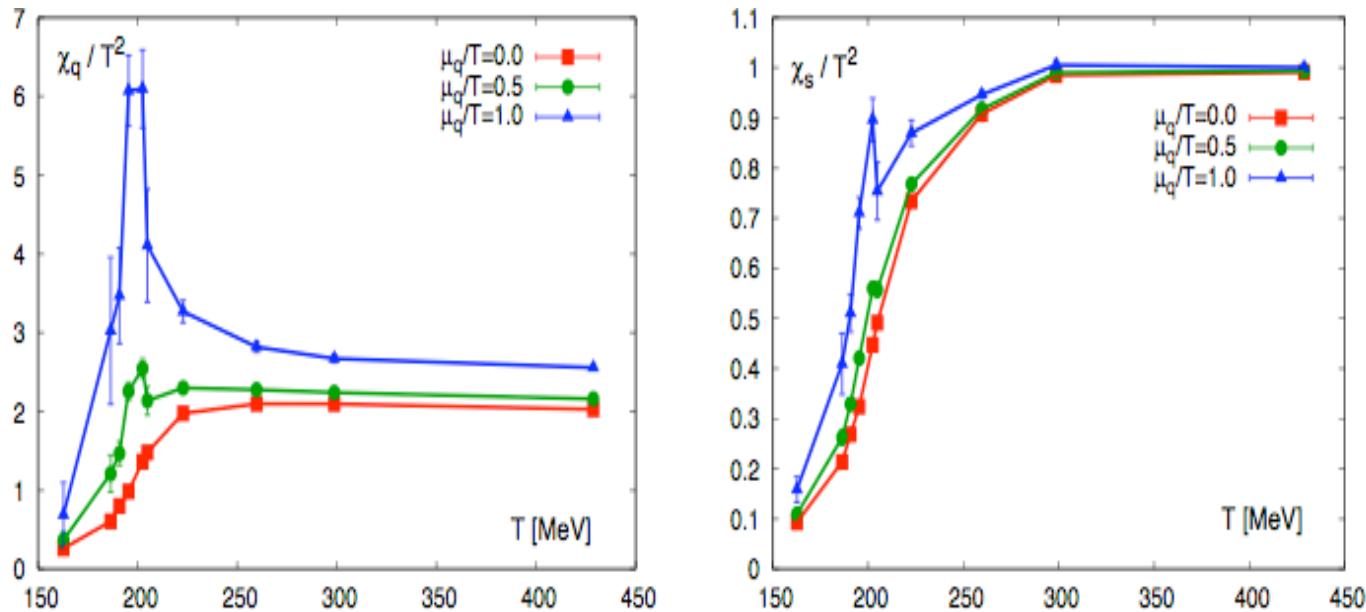
# Observable I: Quark Scaling



- $m_\phi \sim m_p \sim 1 \text{ GeV}$
- $s\bar{s} \Rightarrow \phi$  not  $K^+K^- \Rightarrow \phi$
- $\sigma_{\phi h} \ll \sigma_{p\pi, \pi\pi}$

In the hadronic case, no number of quark scaling and the value of  $v_2$  of  $\phi$  will be small.

# Observable II: $\chi_q, \chi_s$



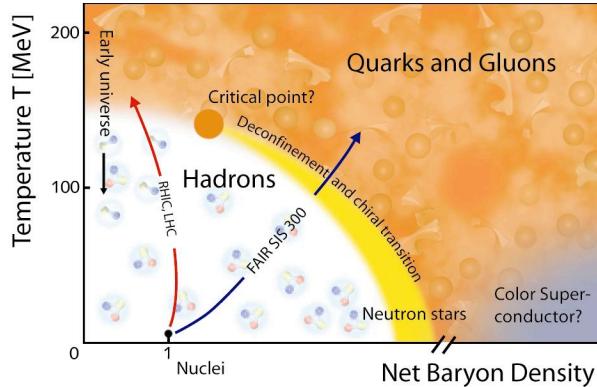
Event by event:

1. net-proton Kurtosis  $K_p(E)$
2. two proton correlation functions  $C_2(E)$
3. ratio of the d/p
4. ratio of K/p

$$K_p = \frac{\langle N_p^4 \rangle - 3\langle N_p^2 \rangle^2}{\langle N_p^2 \rangle}$$

Gavai and Gupta, 05; M. Cheng et al., arXiv:0811.1006  
S. Gupta; F. Karsch, INT, 2008

# STAR Physics Focus



## 1) Heavy-ion program

- Study ***medium properties, EoS***
- pQCD in hot and dense medium

## 2) Beam energy scan at RHIC

- Search for ***critical point***
- Chiral symmetry restoration

### (1) Heavy quark $v_2$ and $R_{AA}$ :

***Thermalization and EoS parameters***

### (2) Beam energy scan:

***Search for the QCD phase boundary and the possibly critical point***